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[54] **MULTICOLORED LED LIGHTING METHOD AND APPARATUS**

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[51] **Int. Cl.**^{7} **H05B 37/02**

[52] **U.S. Cl.** **315/291**; 315/312; 315/362; 315/292

[58] **Field of Search** .... 315/291, 292, 315/295, 300, 316, 302, 362, 312, 314, 324, 307, 76, 297, 308, 209 R, DIG. 5

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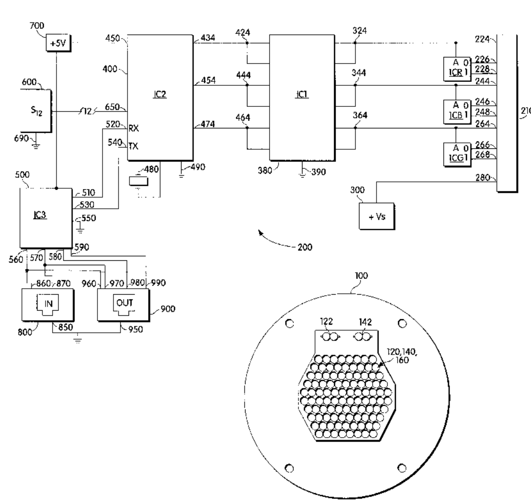
Assistant Examiner—Wilson Lee
Attorney, Agent, or Firm—Foley, Hoag & Eliot, LLP

[57] **ABSTRACT**

The systems and methods described herein relate to LED systems capable of generating light, such as for illumination or display purposes. The light-emitting LEDs may be controlled by a processor to alter the brightness and/or color of the generated light, e.g., by using pulse-width modulated signals. Thus, the resulting illumination may be controlled by a computer program to provide complex, predesigned patterns of light in virtually any environment.

25 Claims, 6 Drawing Sheets



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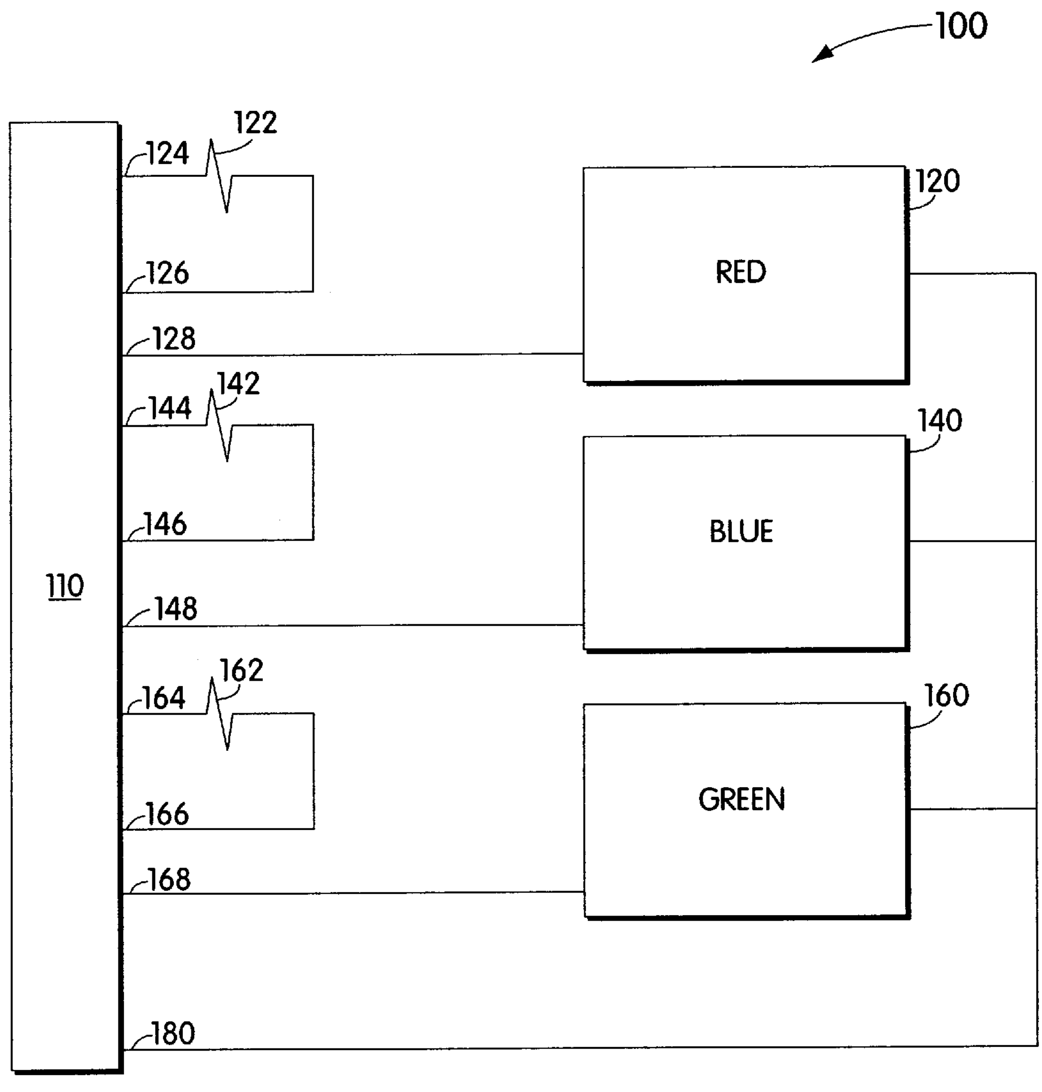
100
122
124
120
126
RED
128
142
144
140
146
BLUE
110
148
162
164
160
166
GREEN
168
180

Fig. 1

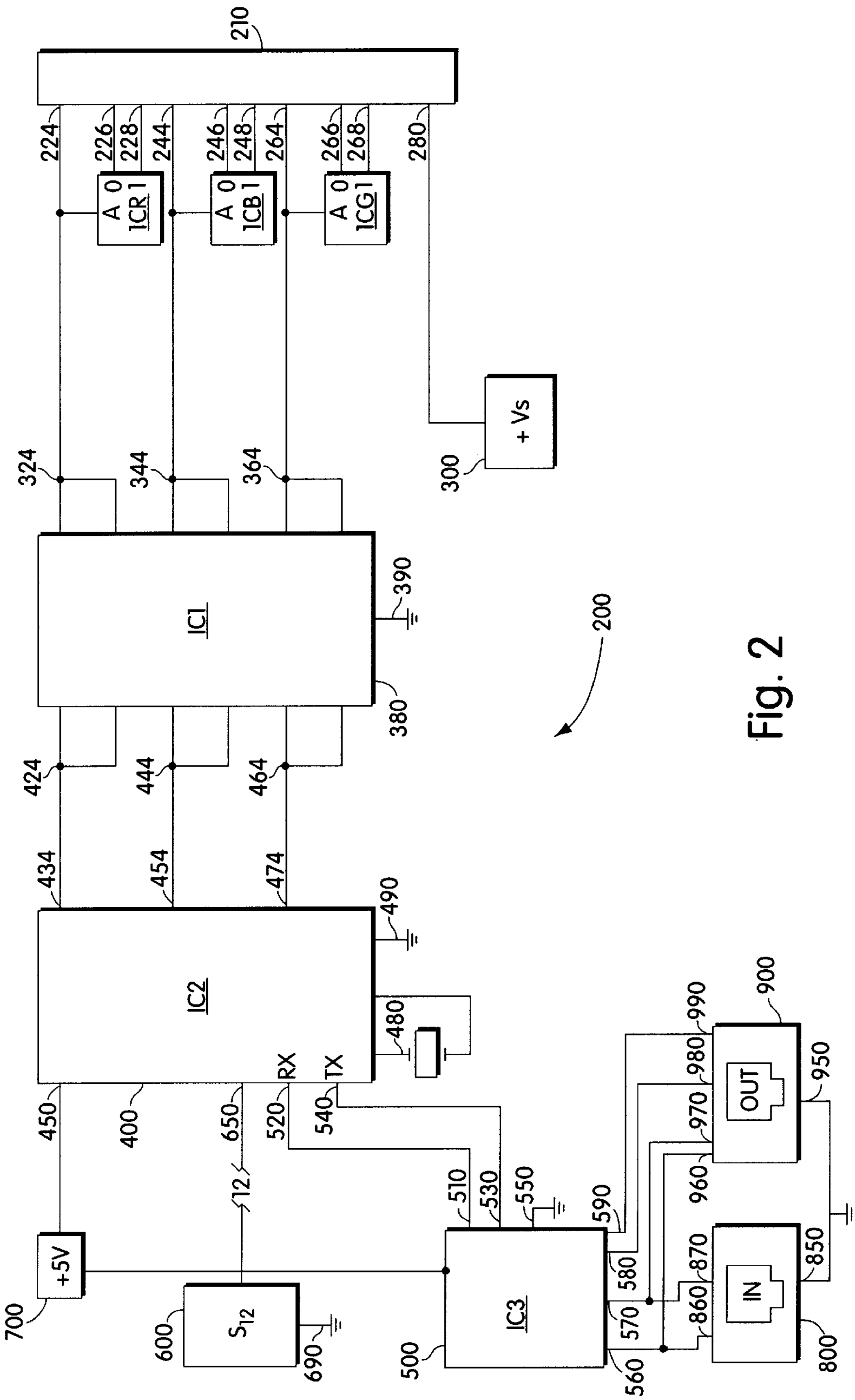
210
224
226
228
244
246
248
264
266
268
280
A 0
ICR1
A 0
ICB1
A 0
ICG1
+Vs
300
324
344
364
IC1
390
380
200
424
444
464
434
454
474
IC2
490
480
RX
TX
450
400
650
520
540
12
510
530
550
590
580
570
560
+5V
700
S_{12}
600
690
IC3
500
OUT
900
990
980
970
960
950
IN
870
860
850
800

Fig. 2

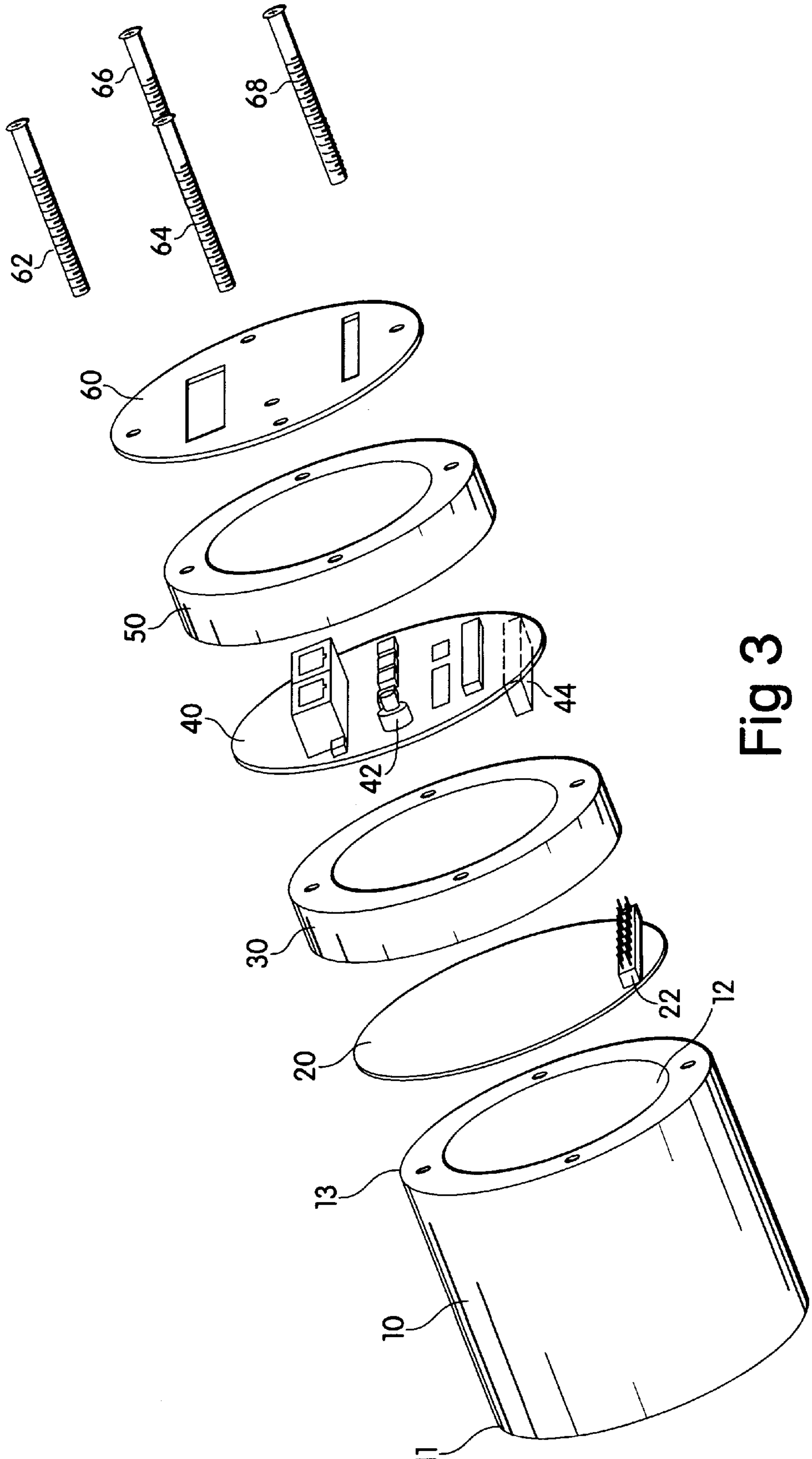

Fig 3

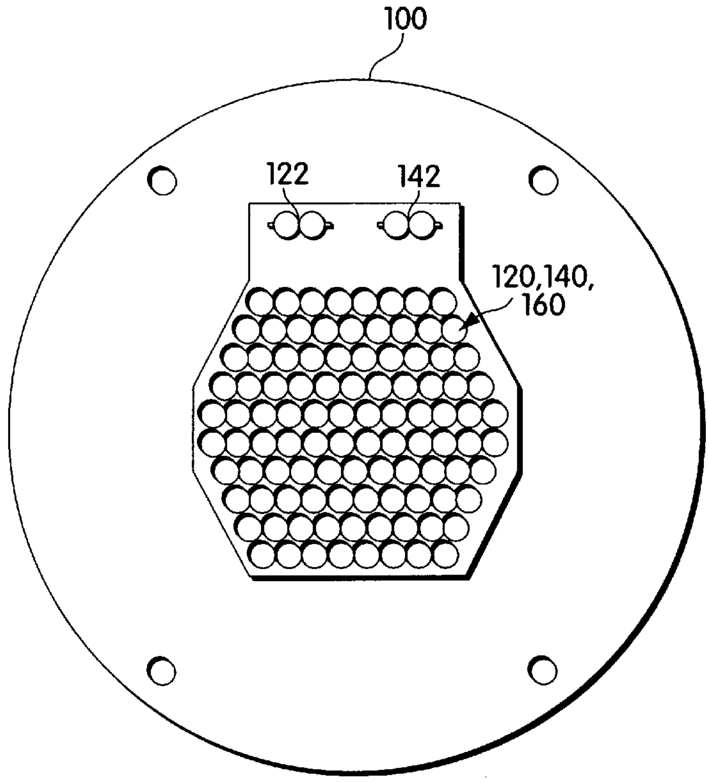

Fig. 4

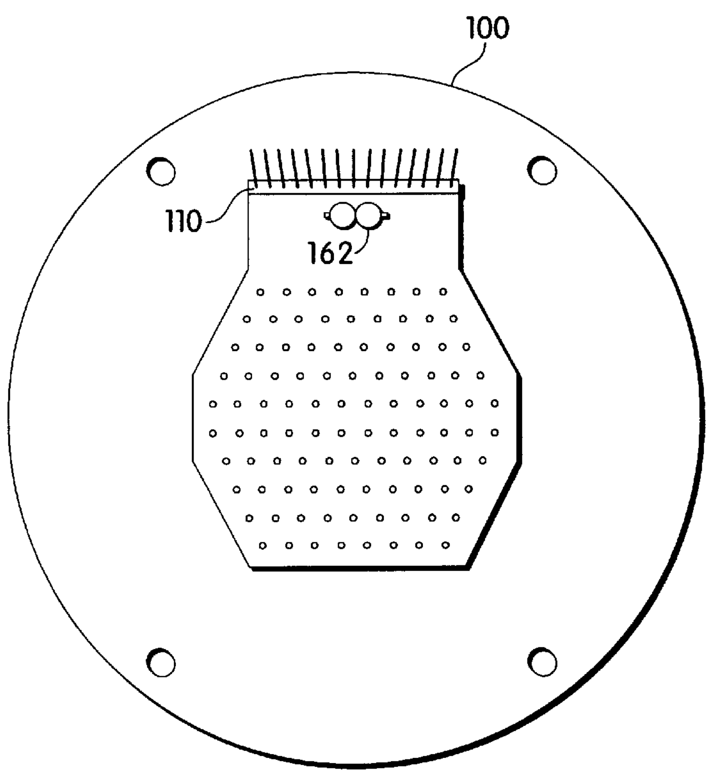

Fig. 5

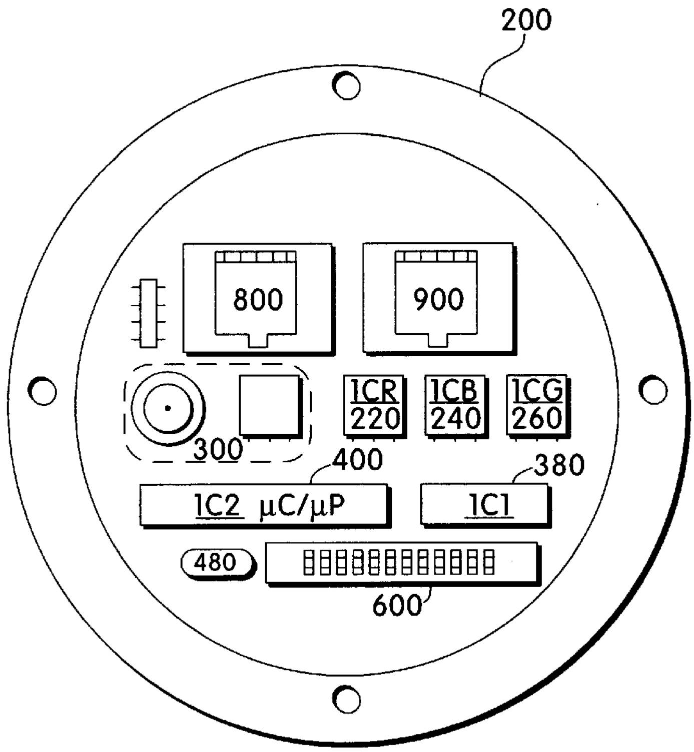
200
800
900
ICR 220
ICB 240
ICG 260
300
400
380
IC2 µC/µP
IC1
480
600

Fig. 6

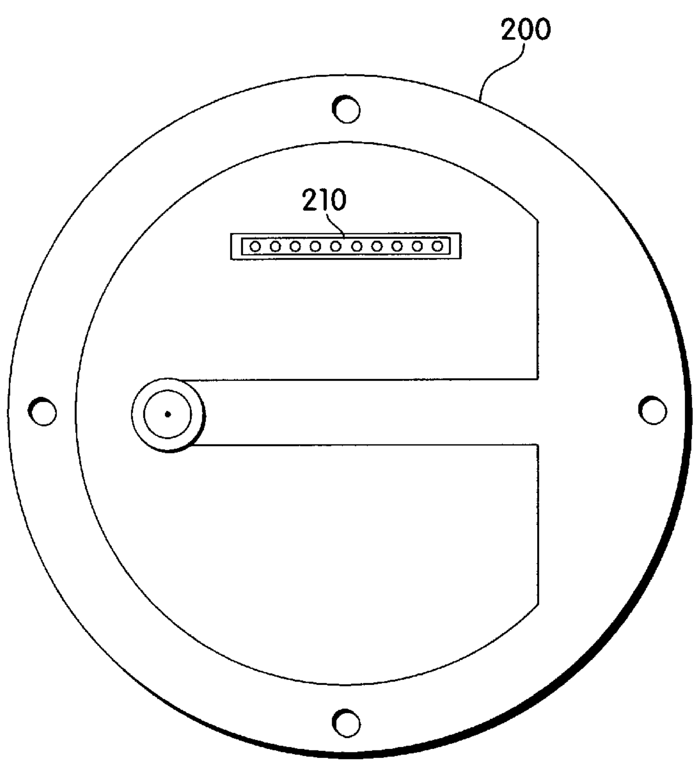
200
210

Fig. 7

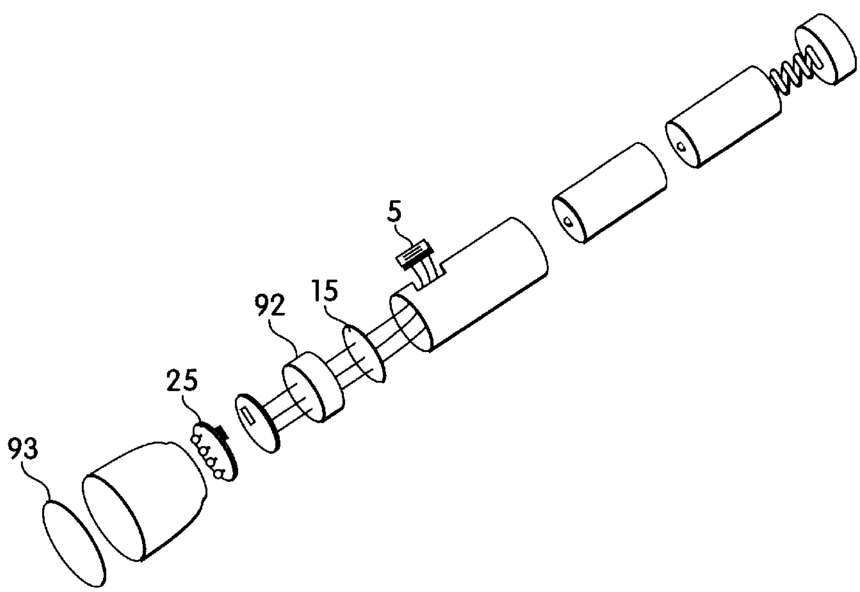
5
92
15
25
93

Fig. 8

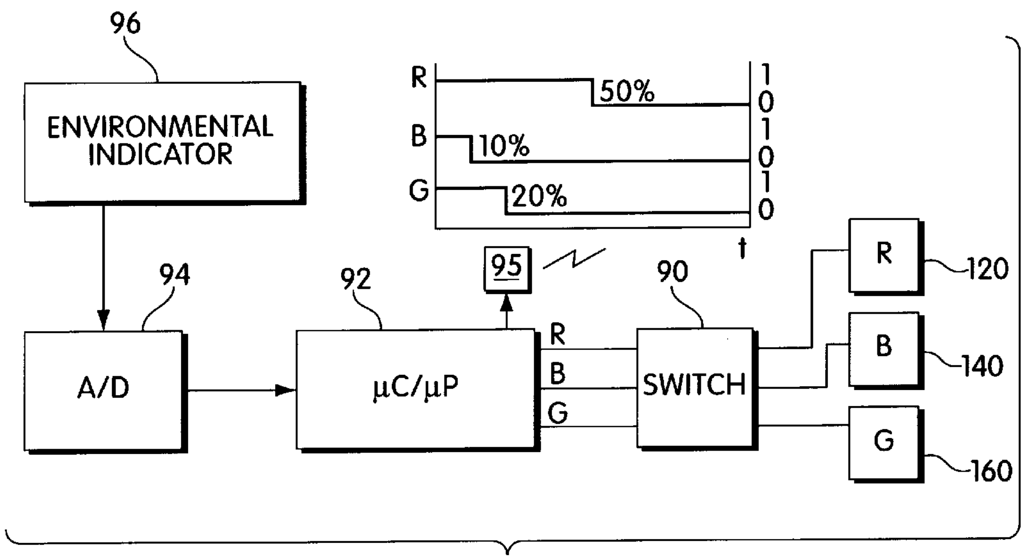
96
ENVIRONMENTAL INDICATOR
R
B
G
50%
10%
20%
1
0
1
0
1
0
t
95
94
92
90
A/D
μC/μP
R
B
G
SWITCH
R
B
G
120
140
160

Fig. 9

MULTICOLORED LED LIGHTING METHOD AND APPARATUS

BACKGROUND OF THE INVENTION

The present invention relates to providing light of a selectable color using LEDs. More particularly, the present invention is a method and apparatus for providing multicolored illumination. More particularly still, the present invention is an apparatus for providing a computer controlled multicolored illumination network capable of high performance and rapid color selection and change.

It is well known that combining the projected light of one color with the projected light of another color will result in the creation of a third color. It is also well known that the three most commonly used primary colors—red, blue and green—can be combined in different proportions to generate almost any color in the visible spectrum. The present invention takes advantage of these effects by combining the projected light from at least two light emitting diodes (LEDs) of different primary colors.

Computer lighting networks are not new. U.S. Pat. No. 5,420,482, issued to Phares, describes one such network that uses different colored LEDs to generate a selectable color. Phares is primarily for use as a display apparatus. However, the apparatus has several disadvantages and limitations. First, each of the three color LEDs in Phares is powered through a transistor biasing scheme in which the transistor base is coupled to a respective latch register through biasing resistors. The three latches are all simultaneously connected to the same data lines on the data bus. This means it is impossible in Phares to change all three LED transistor biases independently and simultaneously. Also, biasing of the transistors is inefficient because power delivered to the LEDs is smaller than that dissipated in the biasing network. This makes the device poorly suited for efficient illumination applications. The transistor biasing used by Phares also makes it difficult, if not impossible, to interchange groups of LEDs having different power ratings, and hence different intensity levels.

U.S. Pat. No. 4,845,481, issued to Havel, is directed to a multicolored display device. Havel addresses some, but not all of the switching problems associated with Phares. Havel uses a pulse width modulated signal to provide current to respective LEDs at a particular duty cycle. However, no provision is made for precise and rapid control over the colors emitted. As a stand alone unit, the apparatus in Havel suggests away from network lighting, and therefore lacks any teaching as to how to implement a pulse width modulated computer lighting network. Further, Havel does not appreciate the use of LEDs beyond mere displays, such as for illumination.

U.S. Pat. No. 5,184,114, issued to Brown, shows an LED display system. But Brown lacks any suggestion to use LEDs for illumination, or to use LEDs in a configurable computer network environment. U.S. Pat. No. 5,134,387, issued to Smith et al., directed to an LED matrix display, contains similar problems. Its rudimentary current control scheme severely limits the possible range of colors that can be displayed.

It is an object of the present invention to overcome the limitations of the prior art by providing a high performance computer controlled multicolored LED lighting network.

It is a further object of the present invention to provide a unique LED lighting network structure capable of both a linear chain of nodes and a binary tree configuration.

It is still another object of the present invention to provide a unique heat-dissipating housing to contain the lighting units of the lighting network.

It is yet another object of the present invention to provide a current regulated LED lighting apparatus, wherein the apparatus contains lighting modules each having its own maximum current rating and each conveniently interchangeable with one another.

It is a still further object of the present invention to provide a unique computer current-controlled LED lighting assembly for use as a general illumination device capable of emitting multiple colors in a continuously programmable 24-bit spectrum.

It is yet a still further object of the present invention to provide a unique flashlight, inclinometer, thermometer, general environmental indicator and lightbulb, all utilizing the general computer current-control principles of the present invention.

Other objects of the present invention will be apparent from the detailed description below.

SUMMARY OF THE INVENTION

In brief, the invention herein comprises a pulse width modulated current control for an LED lighting assembly, where each current-controlled unit is uniquely addressable and capable of receiving illumination color information on a computer lighting network. In a further embodiment, the invention includes a binary tree network configuration of lighting units (nodes). In another embodiment, the present invention comprises a heat dissipating housing, made out of a heat-conductive material, for housing the lighting assembly. The heat dissipating housing contains two stacked circuit boards holding respectively the power module and the light module. The light module is adapted to be conveniently interchanged with other light modules having programmable current, and hence maximum light intensity, ratings. Other embodiments of the present invention involve novel applications for the general principles described herein.

DESCRIPTION OF THE DRAWINGS

FIG. **1** is a stylized electrical circuit schematic of the light module of the present invention.

FIG. **2** is a stylized electrical circuit schematic of the power module of the present invention.

FIG. **3** is an exploded view of the housing of one of the embodiments of the present invention.

FIG. **4** is a plan view of the LED-containing side of the light module of the present invention.

FIG. **5** is a plan view of the electrical connector side of the light module of the present invention.

FIG. **6** is a plan view of the power terminal side of the power module of the present invention.

FIG. **7** is a plan view of the electrical connector side of the power module of the present invention.

FIG. **8** is an exploded view of a flashlight assembly containing the LED lighting module of the present invention.

FIG. **9** is a control block diagram of the environmental indicator of the present invention.

DETAILED DESCRIPTION

The structure and operation of a preferred embodiment will now be described. It should be understood that many other ways of practicing the inventions herein are available, and the embodiments described herein are exemplary and not limiting. Turning to FIG. **1**, shown is an electrical

schematic representation of a light module **100** of the present invention. FIGS. **4** and **5** show the LED-containing side and the electrical connector side of light module **100**. Light module **100** is self-contained, and is configured to be a standard item interchangeable with any similarly constructed light module. Light module **100** contains a ten-pin electrical connector **110** of the general type. In this embodiment, the connector **110** contains male pins adapted to fit into a complementary ten-pin connector female assembly, to be described below. Pin **180** is the power supply. A source of DC electrical potential enters module **100** on pin **180**. Pin **180** is electrically connected to the anode end of light emitting diode (LED) sets **120**, **140** and **160** to establish a uniform high potential on each anode end.

LED set **120** contains red LEDs, set **140** contains blue and set **160** contains green, each obtainable from the Nichia America Corporation. These LEDs are primary colors, in the sense that such colors when combined in preselected proportions can generate any color in the spectrum. While three primary colors is preferred, it will be understood that the present invention will function nearly as well with only two primary colors to generate any color in the spectrum. Likewise, while the different primary colors are arranged herein on sets of uniformly colored LEDs, it will be appreciated that the same effect may be achieved with single LEDs containing multiple color-emitting semiconductor dies. LED sets **120**, **140** and **160** each preferably contains a serial/parallel array of LEDs in the manner described by Okuno in U.S. Pat. No. 4,298,869, incorporated herein by reference. In the present embodiment, LED set **120** contains three parallel connected rows of nine red LEDs (not shown), and LED sets **140** and **160** each contain five parallel connected rows of five blue and green LEDs, respectively (not shown). It is understood by those in the art that, in general, each red LED drops the potential in the line by a lower amount than each blue or green LED, about 2.1 V, compared to 4.0 V, respectively, which accounts for the different row lengths. This is because the number of LEDs in each row is determined by the amount of voltage drop desired between the anode end at the power supply voltage and the cathode end of the last LED in the row. Also, the parallel arrangement of rows is a fail-safe measure that ensures that the light module **100** will still function even if a single LED in a row fails, thus opening the electrical circuit in that row. The cathode ends of the three parallel rows of nine red LEDs in LED set **120** are then connected in common, and go to pin **128** on connector **110**. Likewise, the cathode ends of the five parallel rows of five blue LEDs in LED set **140** are connected in common, and go to pin **148** on connector **110**. The cathode ends of the five parallel rows of five green LEDs in LED set **160** are connected in common, and go to pin **168** on connector **110**. Finally, on light module **100**, each LED set is associated with a programming resistor that combines with other components, described below, to program the maximum current through each set of LEDs. Between pin **124** and **126** is resistor **122**, 6.2Ω. Between pin **144** and **146** is resistor **142**, 4.7Ω. Between pin **164** and **166** is resistor **162**, 4.7Ω. Resistor **122** programs maximum current through red LED set **120**, resistor **142** programs maximum current through blue LED set **140**, and resistor **162** programs maximum current through green LED set **160**. The values these resistors should take are determined empirically, based on the desired maximum light intensity of each LED set. In the present embodiment, the resistances above program red, blue and green currents of 70, 50 and 50 μA, respectively.

With the electrical structure of light module **100** described, attention will now be given to the electrical structure of power module **200**, shown in FIG. **2**. FIGS. **6** and **7** show the power terminal side and electrical connector side of an embodiment of power module **200**. Like light module **100**, power module **200** is self contained. Interconnection with male pin set **110** is achieved through complementary female pin set **210**. Pin **280** connects with pin **180** for supplying power, delivered to pin **280** from supply **300**. Supply **300** is shown as a functional block for simplicity. In actuality, supply **300** can take numerous forms for generating a DC voltage. In the present embodiment, supply **300** provides 24 Volts through a connection terminal (not shown), coupled to pin **280** through transient protection capacitors (not shown) of the general type. It will be appreciated that supply **300** may also supply a DC voltage after rectification and/or voltage transformation of an AC supply, as described more fully in U.S. Pat. No. 4,298,869.

Also connected to pin connector **210** are three current programming integrated circuits, ICR **220**, ICB **240** and ICG **260**. Each of these is a three terminal adjustable regulator, preferably part number LM317B, available from the National Semiconductor Corporation, Santa Clara, Calif. The teachings of the LM317 datasheet are incorporated herein by reference. Each regulator contains an input terminal, an output terminal and an adjustment terminal, labeled I, O and A, respectively. The regulators function to maintain a constant maximum current into the input terminal and out of the output terminal. This maximum current is pre-programmed by setting a resistance between the output and the adjustment terminals. This is because the regulator will cause the voltage at the input terminal to settle to whatever value is needed to cause 1.25 V to appear across the fixed current set resistor, thus causing constant current to flow. Since each functions identically, only ICR **220** will now be described. First, current enters the input terminal of ICR **220** from pin **228**. Of course, pin **228** in the power module is coupled to pin **128** in the light module, and receives current directly from the cathode end of the red LED set **120**. Since resistor **122** is ordinarily disposed between the output and adjustment terminals of ICR **220** through pins **224**/**124** and **226**/**126**, resistor **122** programs the amount of current regulated by ICR **220**. Eventually, the current output from the adjustment terminal of ICR **220** enters a Darlington driver. In this way, ICR **220** and associated resistor **122** program the maximum current through red LED set **120**. Similar results are achieved with ICB **240** and resistor **142** for blue LED set **140**, and with ICG **260** and resistor **162** for green LED set **160**.

The red, blue and green LED currents enter another integrated circuit, IC1 **380**, at respective nodes **324**, **344** and **364**. IC1 **380** is preferably a high current/voltage Darlington driver, part no. DS2003 available from the National Semiconductor Corporation, Santa Clara, Calif. IC1 **380** is used as a current sink, and functions to switch current between respective LED sets and ground **390**. As described in the DS2003 datasheet, incorporated herein by reference, IC1 contains six sets of Darlington transistors with appropriate on-board biasing resistors. As shown, nodes **324**, **344** and **364** couple the current from the respective LED sets to three pairs of these Darlington transistors, in the well known manner to take advantage of the fact that the current rating of IC1 **380** may be doubled by using pairs of Darlington transistors to sink respective currents. Each of the three on-board Darlington pairs is used in the following manner as a switch. The base of each Darlington pair is coupled to signal inputs **424**, **444** and **464**, respectively. Hence, input **424** is the signal input for switching current through node **324**, and thus the red LED set **120**. Input **444** is the signal

input for switching current though node **344**, and thus the blue LED set **140**. Input **464** is the signal input for switching current through node **364**, and thus the green LED set **160**. Signal inputs **424**, **444** and **464** are coupled to respective signal outputs **434**, **454** and **474** on microcontroller IC2 **400**, as described below. In essence, when a high frequency square wave is incident on a respective signal input, IC1 **380** switches current through a respective node with the identical frequency and duty cycle. Thus, in operation, the states of signal inputs **424**, **444** and **464** directly correlate with the opening and closing of the power circuit through respective LED sets **120**, **140** and **160**.

The structure and operation of microcontroller IC2 **400** will now be described. Microcontroller IC2 **400** is preferably a MICROCHIP brand PIC16C63, although almost any properly programmed microcontroller or microprocessor can perform the software functions described herein. The main function of microcontroller IC2 **400** is to convert numerical data received on serial Rx pin **520** into three independent high frequency square waves of uniform frequency but independent duty cycles on signal output pins **434**, **454** and **474**. The FIG. **2** representation of microcontroller IC2 **400** is partially stylized, in that persons of skill in the art will appreciate that certain of the twenty-eight standard pins have been omitted or combined for greatest clarity.

Microcontroller IC2 **400** is powered through pin **450**, which is coupled to a 5 Volt source of DC power **700**. Source **700** is preferably driven from supply **300** through a coupling (not shown) that includes a voltage regulator (not shown). An exemplary voltage regulator is the LM340 3-terminal positive regulator, available from the National Semiconductor Corporation, Santa Clara, Calif. The teachings of the LM340 datasheet are hereby incorporated by reference. Those of skill in the art will appreciate that most microcontrollers, and many other independently powered digital integrated circuits, are rated for no more than a 5 Volt power source. The clock frequency of microcontroller IC2 **400** is set by crystal **480**, coupled through appropriate pins. Pin **490** is the microcontroller IC2 **400** ground reference.

Switch **600** is a twelve position dip switch that may be alterably and mechanically set to uniquely identify the microcontroller IC2 **400**. When individual ones of the twelve mechanical switches within dip switch **600** are closed, a path is generated from corresponding pins **650** on microcontroller IC2 **400** to ground **690**. Twelve switches create 2^{12} possible settings, allowing any microcontroller IC2 **400** to take on one of 4096 different IDs, or addresses. In the preferred embodiment, only nine switches are actually used because the DMX-512 protocol, discussed below, is employed.

Once switch **600** is set, microcontroller IC2 **400** "knows" its unique address ("who am I"), and "listens" on serial line **520** for a data stream specifically addressed to it. A high speed network protocol, preferably a DMX protocol, is used to address network data to each individually addressed microcontroller IC2 **400** from a central network controller (not shown). The DMX protocol is described in a United States Theatre Technology, Inc. publication entitled "DMX512/1990 Digital Data Transmission Standard for Dimmers and Controllers," incorporated herein by reference. Basically, in the network protocol used herein, a central controller (not shown) creates a stream of network data consisting of sequential data packets. Each packet first contains a header, which is checked for conformance to the standard and discarded, followed by a stream of sequential bytes representing data for sequentially addressed devices. For instance, if the data packet is intended for light number fifteen, then fourteen bytes from the data stream will be discarded, and the device will save byte number fifteen. If as in the preferred embodiment, more than one byte is needed, then the address is considered to be a starting address, and more than one byte is saved and utilized. Each byte corresponds to a decimal number 0 to 255, linearly representing the desired intensity from Off to Full. (For simplicity, details of the data packets such as headers and stop bits are omitted from this description, and will be well appreciated by those of skill in the art.) This way, each of the three LED colors is assigned a discrete intensity value between 0 and 255. These respective intensity values are stored in respective registers within the memory of microcontroller IC2 **400** (not shown). Once the central controller exhausts all data packets, it starts over in a continuous refresh cycle. The refresh cycle is define by the standard to be a minimum of 1196 microseconds, and a maximum of 1 second.

Microcontroller IC2 **400** is programmed continually to "listen" for its data stream. When microcontroller IC2 **400** is "listening," but before it detects a data packet intended for it, it is running a routine designed to create the square wave signal outputs on pins **434**, **454** and **474**. The values in the color registers determine the duty cycle of the square wave. Since each register can take on a value from 0 to 255, these values create **256** possible different duty cycles in a linear range from 0% to 100%. Since the square wave frequency is uniform and determined by the program running in the microcontroller IC2 **400**, these different discrete duty cycles represent variations in the width of the square wave pulses. This is known as pulse width modulation (PWM).

The PWM interrupt routine is implemented using a simple counter, incrementing from 0 to 255 in a cycle during each period of the square wave output on pins **434**, **454** and **474**. When the counter rolls over to zero, all three signals are set high. Once the counter equals the register value, signal output is changed to low. When microcontroller IC2 **400** receives new data, it freezes the counter, copies the new data to the working registers, compares the new register values with the current count and updates the output pins accordingly, and then restarts the counter exactly where it left off. Thus, intensity values may be updated in the middle of the PWM cycle. Freezing the counter and simultaneously updating the signal outputs has at least two advantages. First, it allows each lighting unit to quickly pulse/strobe as a strobe light does. Such strobing happens when the central controller sends network data having high intensity values alternately with network data having zero intensity values at a rapid rate. If one restarted the counter without first updating the signal outputs, then the human eye would be able to perceive the staggered deactivation of each individual color LED that is set at a different pulse width. This feature is not of concern in incandescent lights because of the integrating effect associated with the heating and cooling cycle of the illumination element. LEDs, unlike incandescent elements, activate and deactivate essentially instantaneously in the present application. The second advantage is that one can "dim" the LEDs without the flickering that would otherwise occur if the counter were reset to zero. The central controller can send a continuous dimming signal when it creates a sequence of intensity values representing a uniform and proportional decrease in light intensity for each color LED. If one did not update the output signals before restarting the counter, there is a possibility that a single color LED will go through nearly two cycles without experiencing the zero current state of its duty cycle. For instance, assume the red register is set at 4 and the counter

is set at 3 when it is frozen. Here, the counter is frozen just before the "off" part of the PWM cycle is to occur for the red LEDs. Now assume that the network data changes the value in the red register from 4 to 2 and the counter is restarted without deactivating the output signal. Even though the counter is greater than the intensity value in the red register, the output state is still "on", meaning that maximum current is still flowing through the red LEDs. Meanwhile, the blue and green LEDs will probably turn off at their appropriate times in the PWM cycle. This would be perceived by the human eye as a red flicker in the course of dimming the color intensities. Freezing the counter and updating the output for the rest of the PWM cycle overcomes these disadvantages, ensuring the flicker does not occur.

The network interface for microcontroller IC2 **400** will now be described. Jacks **800** and **900** are standard RJ-8 network jacks. Jack **800** is used as an input jack, and is shown for simplicity as having only three inputs: signal inputs **860**, **870** and ground **850**. Network data enters jack **800** and passes through signal inputs **860** and **870**. These signal inputs are then coupled to IC3 **500**, which is an RS-485/RS-422 differential bus repeater of the standard type, preferably a DS96177 from the National Semiconductor Corporation, Santa Clara, Calif. The teachings of the DS96177 datasheet are hereby incorporated by reference. The signal inputs **860**, **870** enter IC3 **500** at pins **560**, **570**. The data signal is passed through from pin **510** to pin **520** on microcontroller IC2 **400**. The same data signal is then returned from pin **540** on IC2 **400** to pin **530** on IC3 **500**. Jack **900** is used as an output jack and is shown for simplicity as having only five outputs: signal outputs **960**, **970**, **980**, **990** and ground **950**. Outputs **960** and **970** are split directly from input lines **860** and **870**, respectively. Outputs **980** and **990** come directly from IC3 **500** pins **580** and **590**, respectively. It will be appreciated that the foregoing assembly enables two network nodes to be connected for receiving the network data. Thus, a network may be constructed as a daisy chain, if only single nodes are strung together, or as a binary tree, if two nodes are attached to the output of each single node.

From the foregoing description, one can see that an addressable network of LED illumination or display units can be constructed from a collection of power modules each connected to a respective light module. As long as at least two primary color LEDs are used, any illumination or display color may be generated simply by preselecting the light intensity that each color emits. Further, each color LED can emit light at any of 255 different intensities, depending on the duty cycle of PWM square wave, with a full intensity pulse generated by passing maximum current through the LED. Further still, the maximum intensity can be conveniently programmed simply by adjusting the ceiling for the maximum allowable current using programming resistances for the current regulators residing on the light module. Light modules of different maximum current ratings may thereby be conveniently interchanged.

The foregoing embodiment may reside in any number of different housings. A preferred housing for an illumination unit is described. Turning now to FIG. **3**, there is shown an exploded view of an illumination unit of the present invention comprising a substantially cylindrical body section **10**, a light module **20**, a conductive sleeve **30**, a power module **40**, a second conductive sleeve **50**, and an enclosure plate **60**. It is to be assumed here that the light module **20** and the power module **40** contain the electrical structure and software of light module **100** and power module **200**, described above. Screws **62**, **64**, **66**, **68** allow the entire apparatus to be mechanically connected. Body section **10**, conductive sleeves **30** and **50** and enclosure plate **60** are preferably made from a material that conducts heat, most preferably aluminum. Body section **10** has an open end **11** a reflective interior portion **12** and an illumination end **13** to which module **20** is mechanically affixed. Light module **20** is disk shaped and has two sides. The illumination side (not shown) comprises a plurality of LEDs of different primary colors. The connection side holds an electrical connector male pin assembly **22**. Both the illumination side and the connection side are coated with aluminum surfaces to better allow the conduction of heat outward from the plurality of LEDs to the body section **10**. Likewise, power module **40** is disk shaped and has every available surface covered with aluminum for the same reason. Power module **40** has a connection side holding an electrical connector female pin assembly **44** adapted to fit the pins from assembly **22**. Power module **40** has a power terminal side holding a terminal **42** for connection to a source of DC power. Any standard AC or DC jack may be used, as appropriate.

Interposed between light module **20** and power module **40** is a conductive aluminum sleeve **30**, which substantially encloses the space between modules **20** and **40**. As shown, a disk-shaped enclosure plate **60** and screws **62**, **64**, **66** and **68** seal all of the components together, and conductive sleeve **50** is thus interposed between enclosure plate **60** and power module **40**. Once sealed together as a unit, the illumination apparatus may be connected to a data network as described above and mounted in any convenient manner to illuminate an area. In operation, preferably a light diffusing means will be inserted in body section **10** to ensure that the LEDs on light module **20** appear to emit a single uniform frequency of light.

From the foregoing, it will be appreciated that PWM current control of LEDs to produce multiple colors may be incorporated into countless environments, with or without networks. For instance, FIG. **8** shows a hand-held flashlight can be made to shine any conceivable color using an LED assembly of the present invention. The flashlight contains an external adjustment means **5**, that may be for instance a set of three potentiometers coupled to an appropriately programmed microcontroller **92** through respective A/D conversion means **15**. Each potentiometer would control the current duty cycle, and thus the illumination intensity, of an individual color LED on LED board **25**. With three settings each capable of generating a different byte from 0 to 255, a computer-controlled flashlight may generate twenty-four bit color. Of course, three individual potentiometers can be incorporated into a single device, such as a track ball or joystick, so as to be operable as a single adjuster. Further, it is not necessary that the adjustment means must be a potentiometer. For instance, a capacitive or resistive thumb plate may also be used to program the two or three registers necessary to set the color. A lens assembly **93** may be provided for reflecting the emitted light. A non-hand held embodiment of the present invention may be used as an underwater swimming pool light. Since the present invention can operate at relatively low voltages and low current, it is uniquely suited for safe underwater operation.

Similarly, the present invention may be used as a general indicator of any given environmental condition. FIG. **9** shows the general functional block diagram for such an apparatus. Shown within FIG. **9** is also an exemplary chart showing the duty cycles of the three color LEDs during an exemplary period. As one example of an environmental indicator **96**, the power module can be coupled to an inclinometer. The inclinometer measures general angular

orientation with respect to the earth's center of gravity. The inclinometer's angle signal can be converted through an A/D converter **94** and coupled to the data inputs of the microcontroller **92** in the power module. The microcontroller **92** can then be programmed to assign each discrete angular orientation a different color through the use of a lookup table associating angles with LED color register values. A current switch **90**, coupled to the microcontroller **92**, may be used to control the current supply to LEDs **120**, **140**, and **160** of different colors. The microcontroller **92** may be coupled to a transceiver **95** for transmitting and receiving signals. The "color inclinometer" may be used for safety, such as in airplane cockpits, or for novelty, such as to illuminate the sails on a sailboat that sways in the water. Another indicator use is to provide an easily readable visual temperature indication. For example, a digital thermometer can be connected to provide the microcontroller a temperature reading. Each temperature will be associated with a particular set of register values, and hence a particular color output. A plurality of such "color thermometers" can be located over a large space, such as a storage freezer, to allow simple visual inspection of temperature over three dimensions.

Another use of the present invention is as a lightbulb. Using appropriate rectifier and voltage transformation means, the entire power and light modules may be placed in an Edison-mount (screw-type) lightbulb housing. Each bulb can be programmed with particular register values to deliver a particular color bulb, including white. The current regulator can be pre-programmed to give a desired current rating and thus preset light intensity. Naturally, the lightbulb will have a transparent or translucent section that allows the passage of light into the ambient.

While the foregoing has been a detailed description of the preferred embodiment of the invention, the claims which follow define more freely the scope of invention to which applicant is entitled. Modifications or improvements which may not come within the explicit language of the claims described in the preferred embodiments should be treated as within the scope of invention insofar as they are equivalent or otherwise consistent with the contribution over the prior art and such contribution is not to be limited to specific embodiments disclosed.

We claim:

1. Light apparatus comprising:

a power terminal;

at least one LED coupled to the power terminal;

a current sink coupled to the at least one LED, the current sink comprising an input responsive to an activation signal enables flow of current through the current sink;

an addressable controller having an alterable address, the controller coupled to the input and having timing means for generating the activation signal for a predefined portion of a timing cycle;

the addressable controller further comprising means for receiving data corresponding to the alterable address and indicative of the predefined portion of the timing cycle:

a second LED coupled to the power terminal and the current sink;

the current sink comprising a second input corresponding to the second LED and responsive to a second activation signal;

the addressable controller comprising second timing means for generating the second activation signal for a second predefined portion of the timing cycle, and further comprising second means for receiving data corresponding to the alterable address and indicative of the second predefined portion of a timing cycle.

2. The light apparatus of claim **1** wherein the at least one LED and the second LED comprise different colors.

3. The light apparatus of claim **1** wherein the predefined portion represents the duty cycle of a PWM signal and the timing cycle is the PWM period.

4. A modular LED illumination assembly comprising:

a body portion having an open end, an illumination end, and a reflective interior portion therebetween defining a body portion axis;

a power module adapted to be mechanically attachable to the illumination end substantially along the body portion axis, the power module having a terminal for attachment to a power supply; and

a light module comprising a plurality of LEDs and having an electrical connector removably attachable to the power module, the light module disposed between the illumination end and the power module such that the LEDs optically communicate with the reflective interior portion, so that the reflective interior portion reflects light from the LEDs;

whereby the light module is capable of being conveniently interchanged with a different light module.

5. The assembly of claim **4**, wherein the power module comprises a current regulator for controlling maximum current supplied to the plurality of LED's, and the light module comprises means for programming the current regulator.

6. The assembly of claim **4**, wherein the light module comprises a thermally conductive surface.

7. The assembly of claim **4**, wherein the power module comprises a thermally conductive surface.

8. The assembly of claim **4**, wherein the body portion is substantially cylindrical, and the power module and light module are substantially disk-shaped.

9. The assembly of claim **4** wherein the power module and the light module define a space therebetween and a conductive sleeve disposed between the light module and the power module substantially encloses the space.

10. The assembly of claim **4**, wherein the electrical connector comprises a conductive pin assembly.

11. The assembly of claim **4**, wherein the plurality of LED's comprises a first plurality of LED's of a first color and a second plurality of LED's of a second color.

12. The assembly of claim **11**, wherein the first color and the second colors are different primary colors.

13. The assembly of claim **4**, wherein the power module comprises:

a current sink coupled to the plurality of LED's, the current sink comprising an input responsive to an activation signal that enables flow of current through the current sink;

an addressable controller having an alterable address and coupled to the input, the addressable controller comprising timing means for generating the activation signal for a predefined portion of a timing cycle;

the addressable controller further comprising means for receiving data corresponding to the alterable address and indicative of the predefined portion of a timing cycle.

14. A lighting network comprising a central controller and a plurality of uniquely addressable illumination units, each unit comprising a first color LED and second color LED;

each unit further comprising:

data means for receiving from the central controller network data comprising LED intensity values

addressed to an individual illumination unit and corresponding to respective ones of the first color and second color LED;

memory means for storing intensity values received from said network data corresponding to the first color LED and to the second color LED;

control means for generating a first pulse width modulated signal and a second pulse width modulated signal, both first and second signals having a duty cycle corresponding to the respective intensity values, whereby each of the first and second pulse width modulated signals is alternately in high voltage or a low voltage state;

current switching means for applying current to the first color LED when the first pulse width modulated signal is in one of either the high voltage or the low voltage state, and for applying current to the second color LED when the second pulse width modulated signal is in one of either the high voltage or the low voltage state.

15. The network of claim **14** wherein the first color LED is a plurality of first color LEDs and the second color LED is a plurality of second color LEDs.

16. The network of claim **14** wherein the first color and the second color LEDs are respectively a first primary color LED and a second primary color LED.

17. The network of claim **14** wherein the unit comprises a third color LED, the intensity values addressed to an individual illumination unit further correspond to the third color LED, the control means further generates a third pulse width modulated signal having a duty cycle corresponding to the third color LED intensity value, whereby the third pulse width modulated signal is alternately in a high voltage or a low voltage state, and the current switching means further applies current to the third color LED when the third pulse width modulated signal is in one of either the high voltage or the low voltage state.

18. The network of claim **17** wherein the first color, the second color and the third color are different primary colors.

19. The network of claim **14** wherein the data means comprises a repeater adapted to electrically interconnect each unit to at least two other units to form a path for the network data.

20. The network of claim **19** wherein the repeater is adapted to electrically interconnect each unit to one network data input and to two network data outputs, whereby the network may comprise a binary tree configuration.

21. An illumination apparatus comprising:

a plurality of LEDs of at least two different colors adapted to be coupled to a power source and to a common potential reference;

a current sink interposed between the plurality of LEDs and the common potential reference, the current sink comprising at least two switches corresponding to respective current paths of the at least two different color LEDs;

control means for periodically and independently opening and closing the at least two switches at high frequency and for generating a duty cycle thereby;

a hand-held housing comprising a compartment for containing the power source and common reference potential, and further comprising a lens assembly for reflecting the light emitted from the plurality of LEDs, which housing substantially encloses the plurality of LEDs, the current sink, the control means, and the programming means; and

programming means coupled to the control means for programming respective duty cycle, for each color of the at least two different color LEDs, wherein the duty cycle ranges from a minimum to a maximum, and the programming means is adapted to generate a substantially continuous range of duty cycles between the minimum and the maximum.

22. An illumination apparatus comprising:

a plurality of LEDs of at least two different colors adapted to be coupled to a power source and to a common potential reference;

a current sink interposed between the plurality of LEDs and the common potential reference the current sink comprising at least two switches corresponding to respective current paths of the at least two different color LEDs;

control means for periodically and independently opening and closing the at least two switches at high frequency and for generating a duty cycle thereby; and

programming means coupled to the control means for programming respective duty cycles for each color of the at least two different color LEDs, wherein the duty cycle ranges from a minimum to a maximum, and the programming means is adapted to generate a substantially continuous range of duty cycles between the minimum and the maximum, and wherein the programming means comprises an inclinometer, the inclinometer generating an output signal indicative of the angular orientation of the apparatus, and the control means comprises conversion means for converting the output signal into a numerical value indicative of each respective duty cycle,

whereby different angular orientations produce different color outputs from the plurality of LEDs.

23. An illumination apparatus comprising:

a plurality of LEDs of at least two different colors adapted to be coupled to a power source and to a common potential reference;

a current sink interposed between the plurality of LEDs and the common potential reference, the current sink comprising at least two switches corresponding to respective current paths of the at least two different color LEDs;

control means for periodically and independently opening and closing the at least two switches at high frequency and for generating a duty cycle thereby; and

programming means coupled to the control means for programing respective duty cycles for each color of the at least two different color LEDs, wherein the duty cycle ranges from a minimum to a maximum, and the programming means is adapted to generate a substantially continuous range of duty cycles between the minimum and the maximum, and wherein the programming means comprises a transceiver for receiving an electromagnetic signal containing data that includes a numerical value indicative of each respective duty cycle.

24. An illumination apparatus comprising:

a plurality of LEDs of at least two different colors adapted to be coupled to a power source and to a common potential reference;

a current sink interposed between the plurality of LEDs and the common potential reference, the current sink comprising at least two switches corresponding to respective current paths of the at least two different color LEDs;

control means for periodically and independently opening and closing the at least two switches at high frequency and for generating a duty cycle, thereby; and

programming means coupled to the control means for programming respective duty cycles for each color of the at least two different color LEDs, wherein the duty cycle ranges from a minimum to a maximum, and the programming means is adapted to generate a substantially continuous range of duty cycles between the minimum and the maximum, and wherein the programming means comprises a transceiver for receiving an infrared signal containing data that includes a numerical value indicative of each respective duty cycle.

25. A method for controlling current through an LED assembly comprising the steps of:

providing a memory location;

placing a numerical value in the memory location indicative of the duty cycle of a pulse width modulated waveform;

closing an LED circuit between supply and ground when the waveform is in one state, and opening the LED circuit when the waveform is in the other state;

providing a counter, wherein the pulse width modulated waveform is in the one state when the counter is below the numerical value;

stopping the counter, updating the waveform state, changing the numerical value in the memory location, and restarting the counter, all upon receipt of a new numerical value over a computer network.

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Börner et al.

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(45) **Date of Patent: May 22, 2001**

(54) **LED LIGHTING SYSTEM FOR PRODUCING WHITE LIGHT**

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(52) **U.S. Cl.** **362/231**; 362/545; 362/555; 362/800

(58) **Field of Search** 362/555, 545, 362/231, 235, 324, 800, 227, 230

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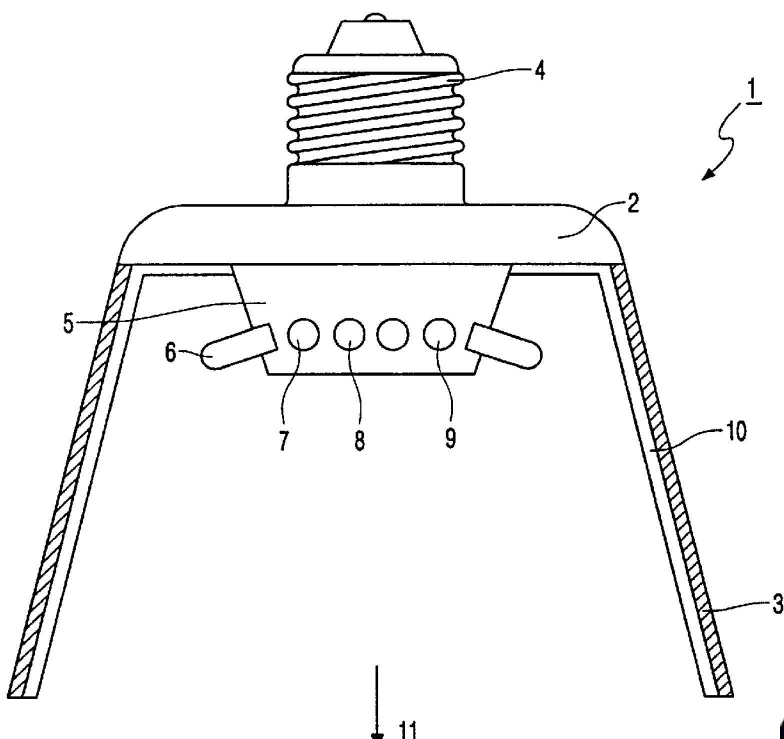
(57) **ABSTRACT**

As a white light source, the lighting system (**1**) has at least three light-emitting diodes (**6**, **7**, **8**) for providing visible light at preselected wavelengths. The invention is characterized in that the lighting system (**1**) is provided with at least one fourth light-emitting diode (**9**) which, in operation, emits visible light in a further wavelength region, the maximum of the spectral emission of the fourth light-emitting diode (**9**) lying in the further wavelength region from 575 to 605 nm. Preferably, the further wavelength region ranges from 585 to 600 nm. Preferably, the color rendition of the lighting system (**1**) is above 60. Preferably, the luminous efficacy of the lighting system (**1**) is above 30 lm/W, preferably above 40 lm/W. In another preferred embodiment, the color temperature of the lighting system (**1**) can be adjusted by selectively switching the light-emitting diodes (**6**, **7**, **8**, **9**).

8 Claims, 2 Drawing Sheets



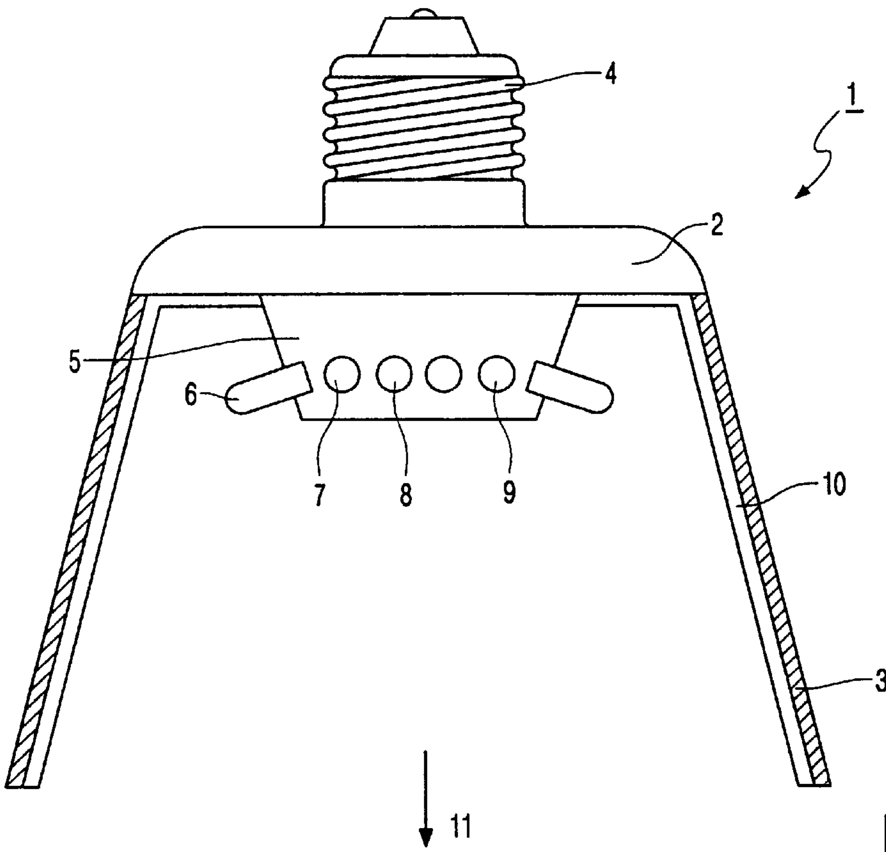


FIG. 1

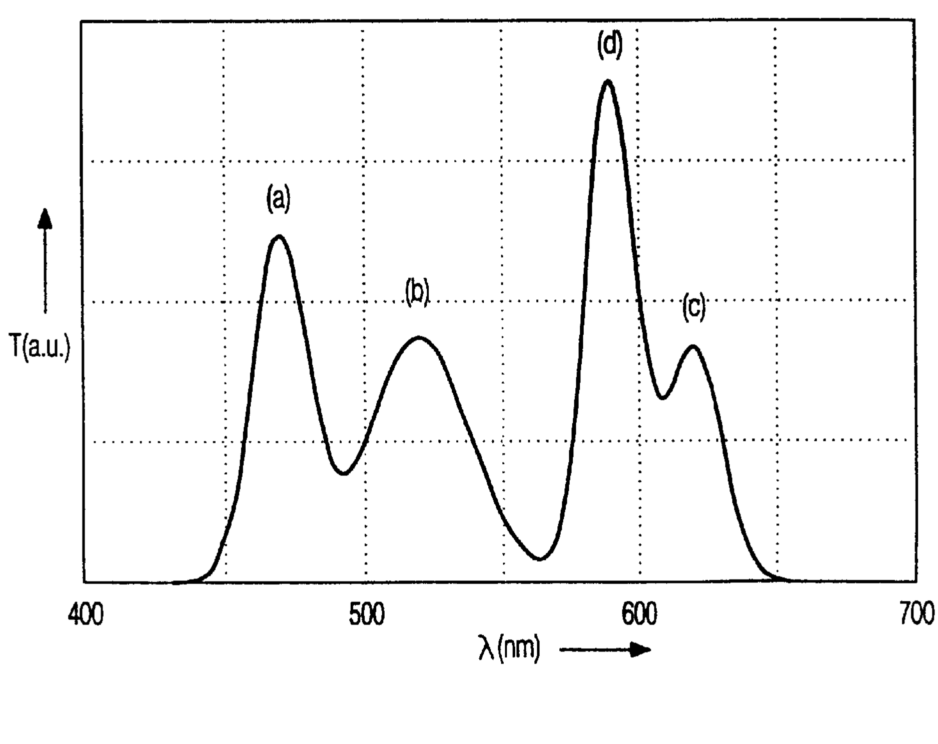


FIG. 2

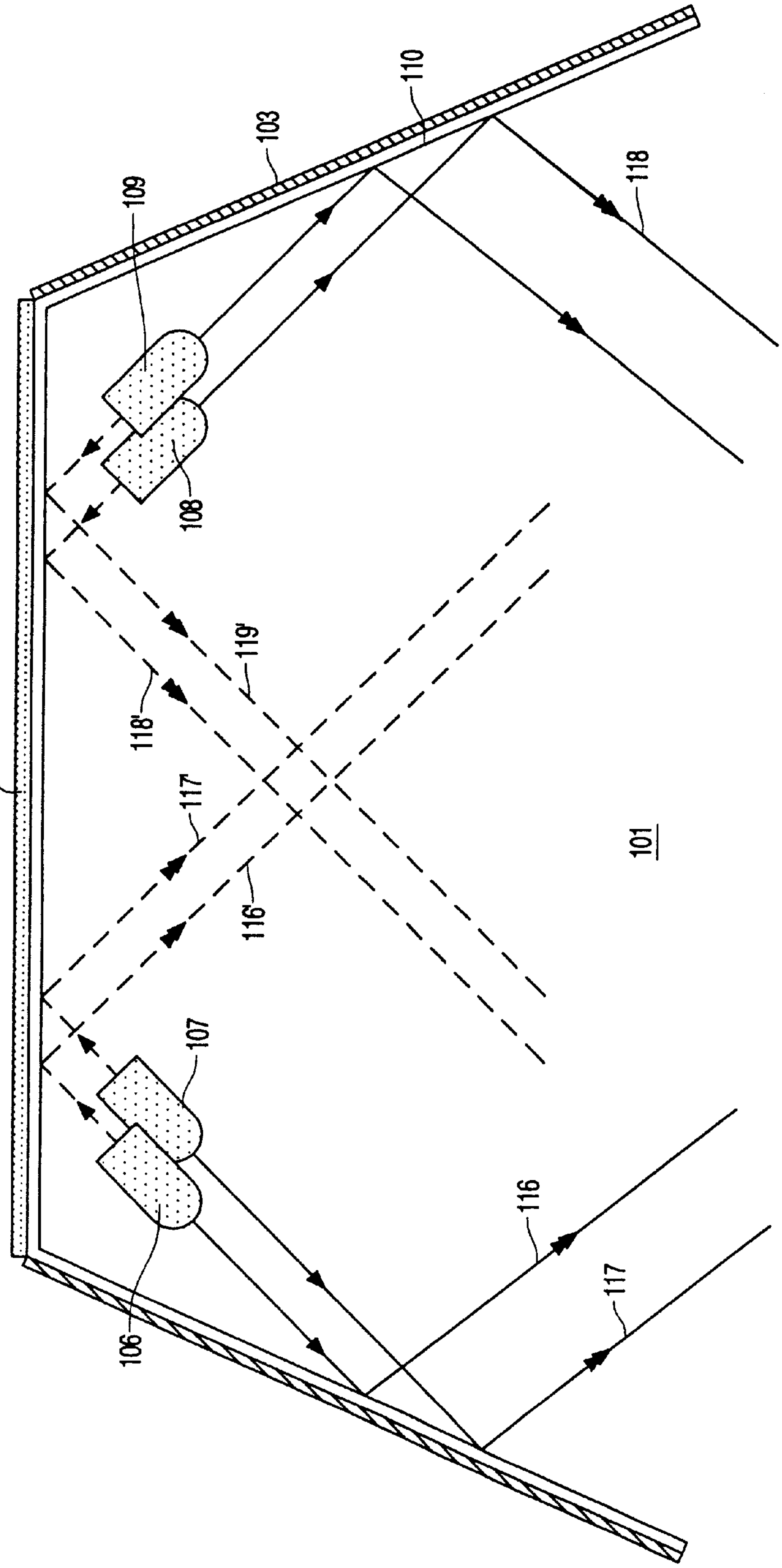


FIG. 3

LED LIGHTING SYSTEM FOR PRODUCING WHITE LIGHT

BACKGROUND OF THE INVENTION

The invention relates to a lighting system for producing white light, which lighting system comprises at least three light-emitting diodes, each one of the light-emitting diodes emitting, in operation, visible light in a preselected wavelength range.

Lighting systems on the basis of light-emitting diodes (LEDs) are used as a source of white light for general lighting applications.

U.S. Pat. No. 5,851,063 discloses a lighting system which employs three LEDs as a light source for; making white light. In this lighting system it is calculated that the maxima of the emission spectra of the LEDs are preferably selected in the wavelength ranges from 455 to 490 mn, 530 to 570 nm and 605 to 630 nm. For such a lighting system it is further calculated that a color rendering index in excess of 80 can be achieved.

Such lighting systems have the drawback that LEDs with spectral maxima in these spectral ranges and, simultaneously, a sufficient energy efficiency are not available. In a lighting system in which such LEDs are employed, particularly the luminous efficacy is adversely influenced.

SUMMARY OF THE INVENTION

It is an object of the invention to provide a lighting system which can be used in practice. The invention further aims at providing a lighting system having a relatively high luminous efficacy.

To achieve this, the lighting system includes at least a fourth light-emitting diode which, in operation, emits visible light in a further wavelength range, the maximum of the spectral emission of the fourth light-emitting diode lying in the further wavelength range from 575 to 605 nm.

By employing four types of LEDs having different spectral ranges, the possibilities of combining LEDs are extended. In order to obtain a lighting system producing white light with a good color rendition, which is based on the three primary colors blue, green and red, it is desirable that the emission maxima of the spectral ranges of the LEDs lie in the ranges from 430 to 490 nm (blue), 530 to 565 nm (green) and 590 to 630 nm (red). In these wavelength ranges, blue and red LEDs with a reasonable luminous efficacy are commercially available, however, green LEDs with the desirable spectral range and comparable luminous efficacy are not or hardly available. Available "green" LEDs having an efficiency which is approximately half that of their blue equivalents emit in the blue-green spectral range between 500 and 525 nm, which does not include the desired spectral range. In addition, as the load at the input of the LED increases, a (further, undesirable) shift towards the blue is observed. Since LEDs with a spectral range in the yellow region (maximum of the spectral emission in the wavelength range from 565 to 605 nm) and a high luminous efficacy are available, a practically usable lighting system producing white light with the desired color rendition is obtained by combining (commercially available) blue, "green" (emission in the blue-green range), yellow and red LEDs. By using commercially available LEDs, a lighting system is obtained which also exhibits a relatively high luminous efficacy.

Highly efficient yellow LEDs on the basis of GaAs have been available for some years and are also increasingly used for signaling purposes, such as rear lights (of vehicles), traffic lights and traffic-signaling systems.

U.S. Pat. No. 5,851,063 also discloses four different types of LEDs as the light source for producing white light, and it is calculated that the maxima of the emission spectra of the LEDs are selected in the wavelength ranges from 440 to 450 nm, 455 to 505 nm, 555 to 565 nm and 610 to 620 nm. These wavelength ranges are based on calculations of the desired light quality on the basis of LEDs with a desired emission spectrum. The known lighting system is apparently not based on commercially available LEDs. The lighting system in accordance with the invention comprises a practically feasible combination of (the spectral characteristics of) known and commercially available LEDs for manufacturing a light source producing white light with a relatively high luminous efficacy.

It is desirable to determine a relatively limited wavelength range within which the maximum of the spectral emission of the fourth light-emitting diode is situated. Preferably, the maximum of the spectral emission of the fourth light-emitting diode lies in the wavelength range from 585 to 600 nm. The use of such yellow LEDs causes the harmony with the other three types of LEDs to be improved. Since the photopic sensitivity of the human eye in the wavelength range is maximal at 555 nm, relatively small variations in the spectral range of the yellow LED have a relatively large effect on the color rendition of the lighting system. A (commercially available) yellow LED having a maximum spectral emission at 595 nm (20 nm FWHM, energy-efficiency 20%) is very suitable.

Preferably, the color rendering index (Ra) of the lighting system is at least equal to or greater than 60($R_a \geqq 60$). By a suitable combination of the spectral emissions of the four light sources, a lighting system is obtained having a relatively high luminous efficacy and a good color rendering index.

Preferably, the luminous efficacy of the lighting system is at least equal to or greater than 30 lm/W. Lighting systems on the basis of LEDs having such an efficiency are commercially attractive. In a particularly preferred embodiment, the luminous efficacy of the lighting system is greater than 40 lm/W. For comparison, a typical 100 W incandescent lamp has a luminous efficacy of 14 lm/W (color temperature 2800 K, color rendering index 100), a 500 W halogen incandescent lamp has a luminous efficacy of approximately 19 lm/W (color temperature 3000 K, color rendering index 100), while a 36 W fluorescent lamp has a luminous efficacy of approximately 89 lm/W (color temperature 4000 K, color rendering index 85). The color rendering index of the lighting system in accordance with the invention is lower than that calculated in the known lighting system, however, the luminous efficacy of the lighting system in accordance with the invention is substantially higher and the lighting system in accordance with the invention is based on a combination of commercially available light-emitting diodes.

Preferably the three light-emitting diodes comprise a blue light-emitting diode, a blue-green light-emitting diode and a red light-emitting diode, and the fourth light-emitting diode includes a yellow light-emitting diode. In this manner, a lighting system is obtained which emits white light with a good color rendition on the basis of four basic colors (blue, blue-green, yellow and red). Preferably, the maximum of the spectral emission of the blue light-emitting diode lies in the wavelength range from 460 to 490 nm, the maximum of the spectral emission of the blue-green light-emitting diode lies

in the wavelength range from 510 to 530 nm, and the maximum of the spectral emission of the red light-emitting diode lies in the wavelength range from 610 to 630 nm. LEDs having such spectral ranges and a relatively high energy efficiency are commercially feasible. By using the yellow-type LEDs, the "mismatch" in the color of the green LED, which emits blue-green light, is compensated.

A point of special interest in the lighting system in accordance with the invention is that, in general, LEDs emit light with a high directivity, while it is desirable for the LEDs to emit (diffuse) light in accordance with a Lambertian radiator.

The invention further aims at improving the blending of light of the lighting system. To achieve this, an alternative embodiment of the lighting system in accordance with the invention is characterized in that the lighting system is further provided with reflection means. The LEDs are provided in the lighting system in such a manner that a substantial part of the light originating from the LEDs cannot directly leave the lighting system, but instead is incident on the reflection means. An advantage of the use of reflection means is that light originating from the (blue and red) LEDs and the (green) light originating from the conversion means is blended. The reflection means are preferably diffusely reflecting reflection means. By directing the light originating from the LEDs to the diffusely reflecting reflection means, the reflected light also acquires the character of a Lambertian radiator. As a result, the blending of the various color components and hence the color rendition of the lighting system are further improved. Furthermore, the reflection means preferably reflect the light without causing a change of the color rendition (white-reflecting reflection means). As a result, undesirable color deviations in the light emitted by the lighting system are precluded.

Preferably, the reflection means comprise a material selected from the group formed by $BaSO_4$, ZnS, ZnO and TiO_2. Such materials are very suitable because their reflection coefficient in the wavelength range from 400 to 800 nm is above 98%, and, in addition, they reflect the light in a diffuse and wavelength-independent manner.

It is further desirable for the color temperature of the lighting system to be variable. An alternative embodiment of the lighting system in accordance with the invention is characterized in that the color temperature of the lighting system is adjustable by separately driving the light-emitting diodes. The color temperature is (electrically) adjustable by separately driving various colors. By suitably switching on and off (diode chains of) LEDs, an adjustable color temperature range from 2000 to 6300 K is obtained.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows, partly in cross-section and in side elevation, an embodiment of the lighting system in accordance with the invention;

FIG. **2** shows the transmission spectrum of an embodiment of the lighting system in accordance with the invention, and

FIG. **3** is a cross-sectional view of an alternative embodiment of the lighting system in accordance with the invention.

The Figures are purely schematic and not drawn to scale. Particularly for clarity, some dimensions are exaggerated strongly. In the Figures, like reference numerals refer to like parts whenever possible.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. **1** shows, a housing **2** accommodating drive electronics (not shown in FIG. **1**) for the light-emitting diodes (LEDs) and a screen **3**. In this example, the housing is provided with a so-called E27 lamp cap **4** having mechanical and electrical contact means which are known per se. On a side of the lighting system **1** facing away from the lamp cap **4**, there is holder **5** on which a number of LEDs **6**, **7**, **8**, **9** are provided. The LEDs **6**, **7**, **8** comprise a collection of blue LEDs **6** (maximum of the spectral emission lies in the wavelength range from 460 to 490 nm), so-called blue-green LEDs **7** (maximum of the spectral emission lies in the wavelength range from 510 to 530 nm), and red LEDs **8** (maximum of the spectral emission lies in the wavelength range from 590 to 630 nm). In accordance with the invention, the LEDs **9** comprise light-emitting diodes which emit yellow light (maximum of the spectral emission lies in the wavelength range from 575 to 605 nm). The LEDs **6**, **7**, **8**, **9** are arranged so that the light that they emit is directed towards the screen **3**. Said screen **3** is provided on a side facing the LEDs **6**, **7**, **8**, **9** with reflection means **10** which diffusely reflect white light. The diffusely reflecting reflection means **10** include, in this example, a layer of $BaSO_4$, which material has a (diffuse) reflection coefficient for visible light of substantially 100%. The reflection means **10** effectively blend the light of the LEDs **6**, **7**, **8**, **9**, said LEDs being positioned relative to the screen **3** in such a manner that said LEDs do not directly emit their light in a direction **11** of the light emitted by the lighting system **1**; instead their light output is directed to an inner side of the screen **3** in such a manner that only reflected light is emitted in the direction **11**.

In order to vary the color temperature of the lighting system **1** and be able to adjust the color temperature in accordance with the requirements, the LEDs can be separately driven, thus causing the proportions of the different colors of light originating from the LEDs to vary.

By way of example, Table I shows a lighting system comprising:

- blue LEDs (make Nichia): emission maximum: 470 nm, half width value (FWHM): 20 nm and lumen equivalent: 68 lm/W;
- blue-green LEDs (make Nichia): emission maximum: 520 nm, FWHM: 40 nm;
- yellow LEDs (make Hewlett Packard): emission maximum: 590 nm, FWHM: 20 nm and lumen equivalent (blue-green+yellow): 483 lm/W;
- red LEDs (make Hewlett Packard): emission maximum: 620 nm, FWHM: 20 nm and lumen equivalent of 263 lm/W.

Column 1 in Table 1 lists various desired values of the color temperature (T_c). Columns 2, 3 and 4 in Table I list the spectral contributions (x) of the three light components (sum of the three spectral contributions x amounts to 1). The spectral contributions of the blue-green and the yellow LEDs are added together in column 3 of Table I. Column 5 of Table I lists the color rendering index (R_a), and column 6 the luminous efficacy (lum. eff.) of the lighting system. Table I shows that the color temperature of the lighting system can be readily adjusted within a very wide range by only changing the distribution of the light sources (particularly of the blue and red LEDs).

Table I Combination of blue and green/yellow and red LEDs in an embodiment of the lighting system in accordance with the invention.

T_c [K]	x [blue]	x [green/yellow]	x [red]	R_a	lum.eff. [lm/W]
2700	0.075	0.575	0.350	71	46.3
2900	0.116	0.577	0.307	70	44.1
4000	0.199	0.621	0.180	66	40.5
5000	0.267	0.609	0.124	63	37.1
6300	0.321	0.614	0.065	59	34.9

In accordance with the measure of the invention, a lighting system based on four types of LEDs is obtained in this manner, which lighting system has a relatively high luminous efficacy (35≦lum. eff.≦50 lm/W) and a relatively good color rendition (60≦R_a70).

FIG. **2** shows the transmission spectrum of an embodiment of the lighting system in accordance with the invention. The transmission T (arbitrary units) is plotted as a the wavelength λ (nm) of visible light for a combination of blue, blue-green, yellow and red LEDs at a color temperature T_c=4000 K (the spectrum in FIG. **2** corresponds to the data in row 4 of Table I). In FIG. **2**, the spectral maximum of the blue LEDs **6** is indicated by (a) and corresponds to a wavelength of 470 nm, the spectral maximum of the blue-green LEDs **7** is indicated by (b) and corresponds to a wavelength of 520 nm, and the spectral maximum of the red LEDs **8** is indicated by (c) and corresponds to a wavelength of 620 mn. In accordance with the invention, the lighting system includes a fourth type of LEDs **9** which, in operation, emits visible light in a further wavelength range. In FIG. **2**, the spectral maximum of the yellow LEDs **9** is indicated by (d) and corresponds to a wavelength of 590 nm. This means that the emission spectrum of the fourth type of LED **9** lies in the further wavelength range of from 575 to 605 nm.

An improvement of the color rendition of the lighting system is obtained by employing deep-red LEDs with a spectral emission spectrum in the wavelength range from 620 to 670 nm.

FIG. **3** very schematically shows an alternative embodiment of the lighting system in accordance with the invention. The lighting system **101** comprises a housing **102** and a screen **103**. In the lighting system **101** there is provided a number of LEDs **106, 107, 108, 109**. For clarity, only four LEDs are shown in FIG. **3**. The LEDs **106, 107, 108** include a collection of blue LEDs **106** (spectral emission 430≦λ≦490 nm), blue-green LEDs (spectral emission 510≦λ≦530 nm) and red LEDs **107** (spectral emission 590≦λ≦630 nm). In accordance with the invention, the LEDs **109** comprise light-emitting diodes which emit yellow light (spectral emission 575≦λ≦605 nm). The LEDs **106, 107, 108, 109** are arranged so that the light which they emit is directed at the screen **3** (the direction of the light is schematically indicated by the continuous lines representing light rays in FIG. **3**). The sides of the housing **102** and the screen **103** facing the LEDs are provided with reflection means **110** (which diffusely reflect white light). By directing the light originating from the LEDs at the diffusely reflecting reflection means **110**, effective blending of the various colors is brought about, and, in addition, the reflected light acquires the character of a Lambertian radiator. The path of the light rays emitted by the LEDs **106, 107, 108, 109** and of the reflected light is diagrammatically indicated by continuous lines in FIG. **3**. Since the housing too is provided with the reflection means **110**, also the light emitted backwards by the LEDs is reflected and, thus, contributes to the luminous efficacy of the lighting system. Such a lighting system is provided, for example, with 40 to 100 diodes, in a ratio of 2 blue LEDs : 4 blue-green LEDs: 2 yellow LEDs: 1 red LED, the relative contributions of LEDs being set in accordance with the values listed in Table I so as to obtain a desired color temperature. The diodes are preferably arranged in two double rows, which include an angle smaller than 90° with the housing **102** (schematically shown in FIG. **3**). Light emitted in the forward direction by the LEDs **106, 107, 108, 109** (indicated in FIG. **3** by the arrows **116, 117, 118, 119**) can only leave the lighting system via at least one reflection against the screen **103** provided with the reflection means **110**, for example a white pigment such as $BaSO_4$. By virtue of the oblique arrangement of the LEDs, also the light emitted in the backward direction by the LEDs **106, 107, 108, 109** can leave the lighting system **101** via multiple reflection (indicated in FIG. **3** by the arrows **116', 117', 118', 119'**), thereby effectively contributing to the luminous efficacy of the lighting system **101**.

The lighting system in accordance with the invention has the advantage that a relatively high luminous efficacy (≧30 lm/W) is obtained in combination with a good color rendition (60≦R_a≦75) of the system and a long service life (≦75,000 hours).

It will be obvious that within the scope of the invention many variations are possible to those skilled in the art.

The invention is embodied in each novel characteristic and each combination of characteristics.

What is claimed is:

1. A lighting system for producing white light, which lighting system comprises four light-emitting diodes, each one of the light-emitting diodes emitting, in operation, visible light in a preselected wavelength range, one of the said light emitting diodes having a maximum of spectral emission lying in the wavelength range from 575 to 605 nm, wherein the luminous efficacy of the lighting system is greater than 40 lm/W.

2. A lighting system as claimed in claim **1**, wherein the maximum of the spectral emission of said one of the said light emitting diodes lies in the wavelength range from 585 to 600 nm.

3. A lighting system as claimed in claim **1**, wherein a color rendering index of the lighting system is at least 60.

4. A lighting system as claimed in claim **1**, wherein the four light-emitting diodes comprise a blue light-emitting diode, a blue-green light-emitting diode, a red light-emitting diode, and a yellow light-emitting diode.

5. A lighting system as claimed in claim **4**, wherein the maximum of the spectral emission of the blue light-emitting diode lies in the wavelength range from 460 to 490 nm, the maximum of the spectral emission of the blue-green light-emitting diode lies in the wavelength range from 510 to 530 nm, and the maximum of the spectral emission of the red light-emitting diode lies in the wavelength range from 610 to 630 nm.

6. A lighting system as claimed in claim **1**, wherein the lighting system provided with reflection means.

7. A lighting system as claimed in claim **6**, wherein the reflection means comprise a material selected from the group formed by $BaSO_4$, ZnS, ZnO and TiO_2.

8. A lighting system as claimed in claim **1**, wherein the color temperature of the lighting system is adjustable by separately driving the light-emitting diodes.

* * * * *

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(54) **LIGHTING SYSTEM**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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Mar. 10, 1999 (EP) 99200723

(51) **Int. Cl.**7 .... **H05B 43/00**
(52) **U.S. Cl.** **362/235**; 362/227; 362/800; 362/84; 362/293; 362/231; 362/545; 313/499; 313/512; 313/312; 313/313
(58) **Field of Search** 362/227, 800, 362/84, 293, 231, 545; 313/499, 512, 312, 313

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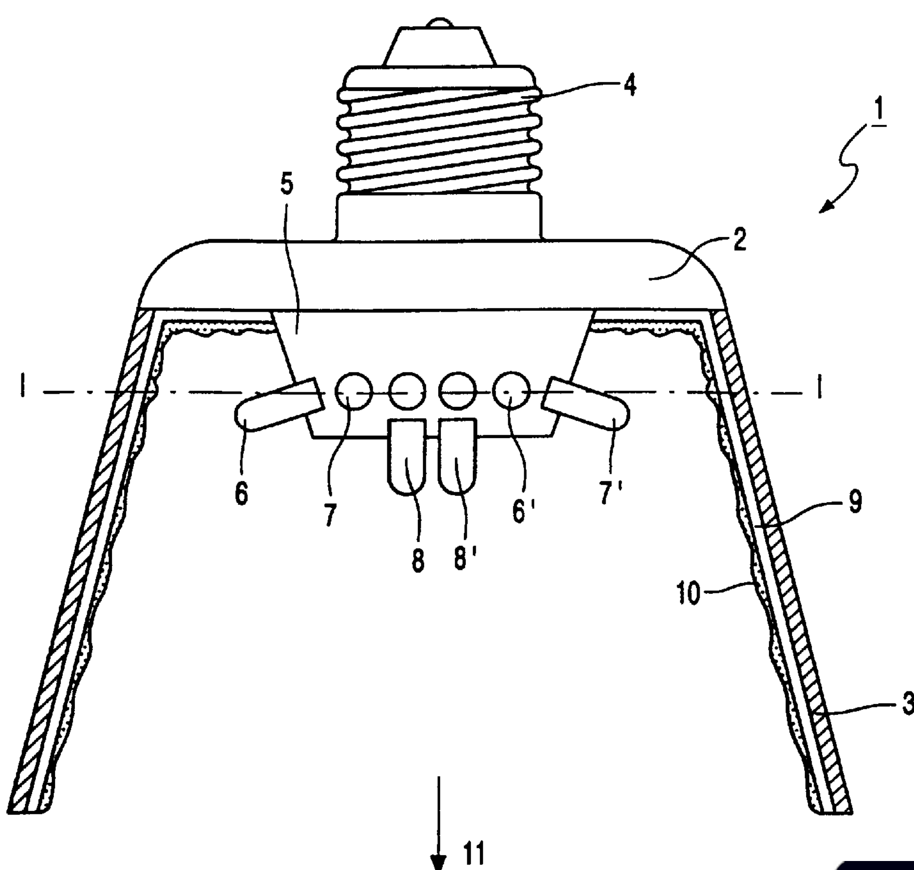
(57) **ABSTRACT**

A lighting system includes at least two light-emitting diodes each emitting, in operation, visible light in a preselected wavelength range. A converter converts part of the visible light emitted by one of the diodes into visible light in a further wavelength range so as to optimize the color rendition of the lighting system. The diodes include a blue light-emitting diode and a red light-emitting diode. Further, the converter includes a luminescent material for converting a portion of the light emitted by the blue light-emitting diode into green light.

20 Claims, 4 Drawing Sheets



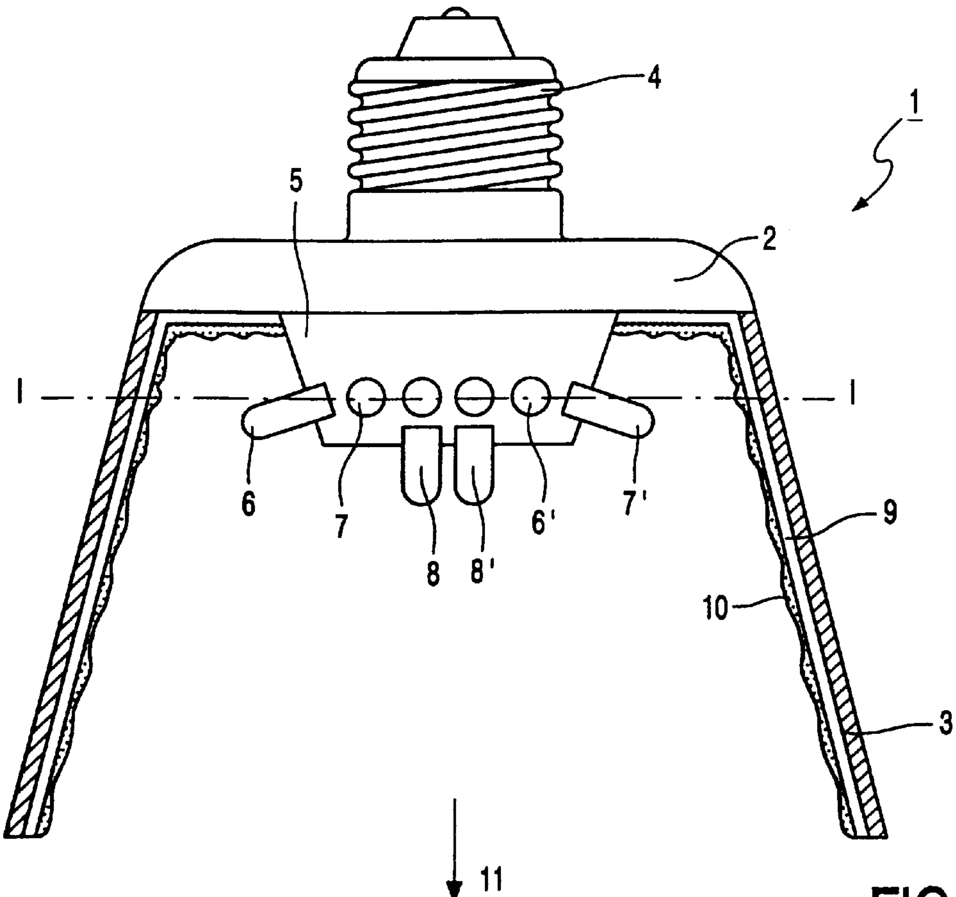


FIG. 1A

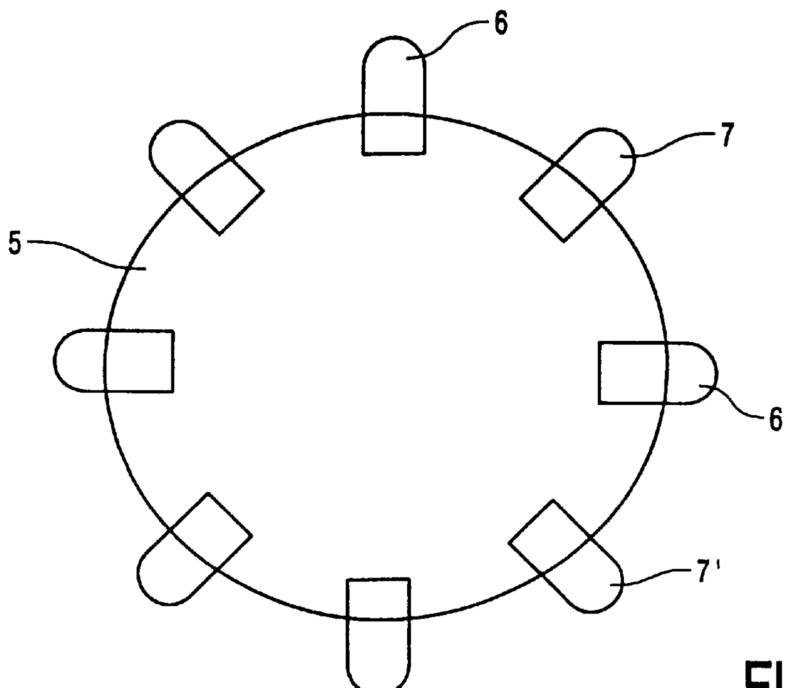


FIG. 1B

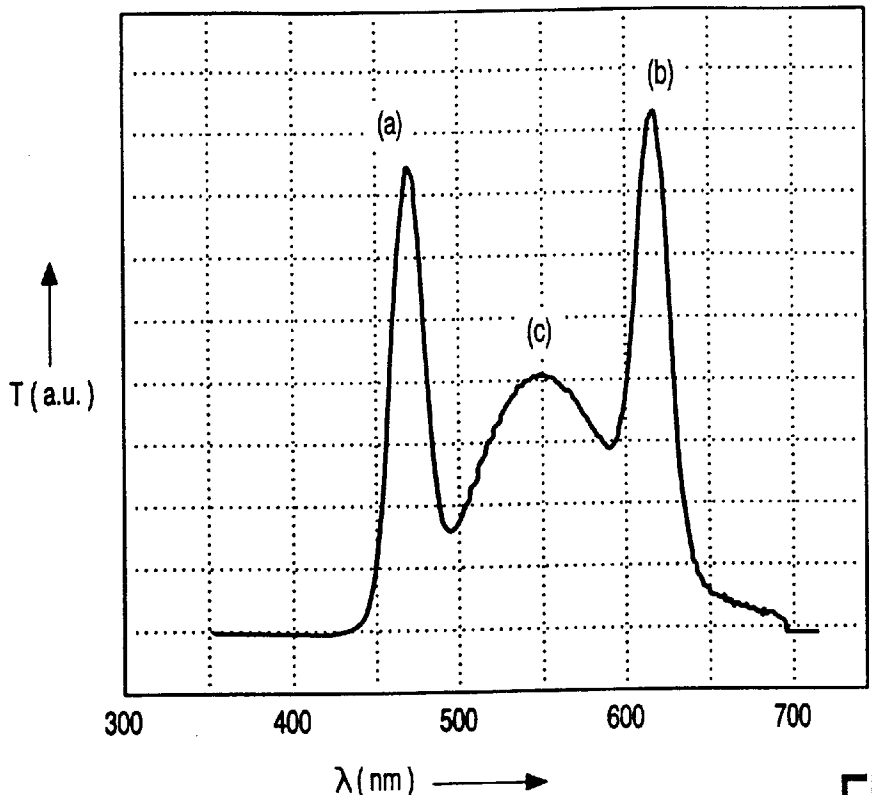

(a)
(b)
(c)
T (a.u.)
300
400
500
600
700
λ (nm)

FIG. 2

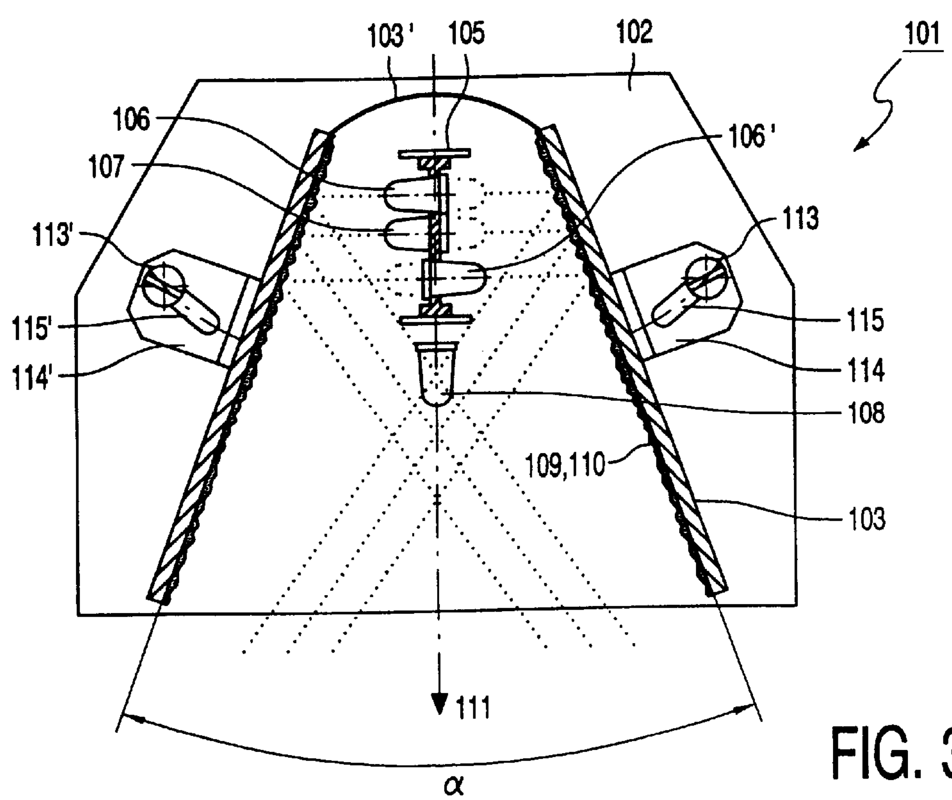

103'
105
102
101
106
106'
107
113'
113
115'
115
114'
114
108
109,110
103
111
α

FIG. 3A

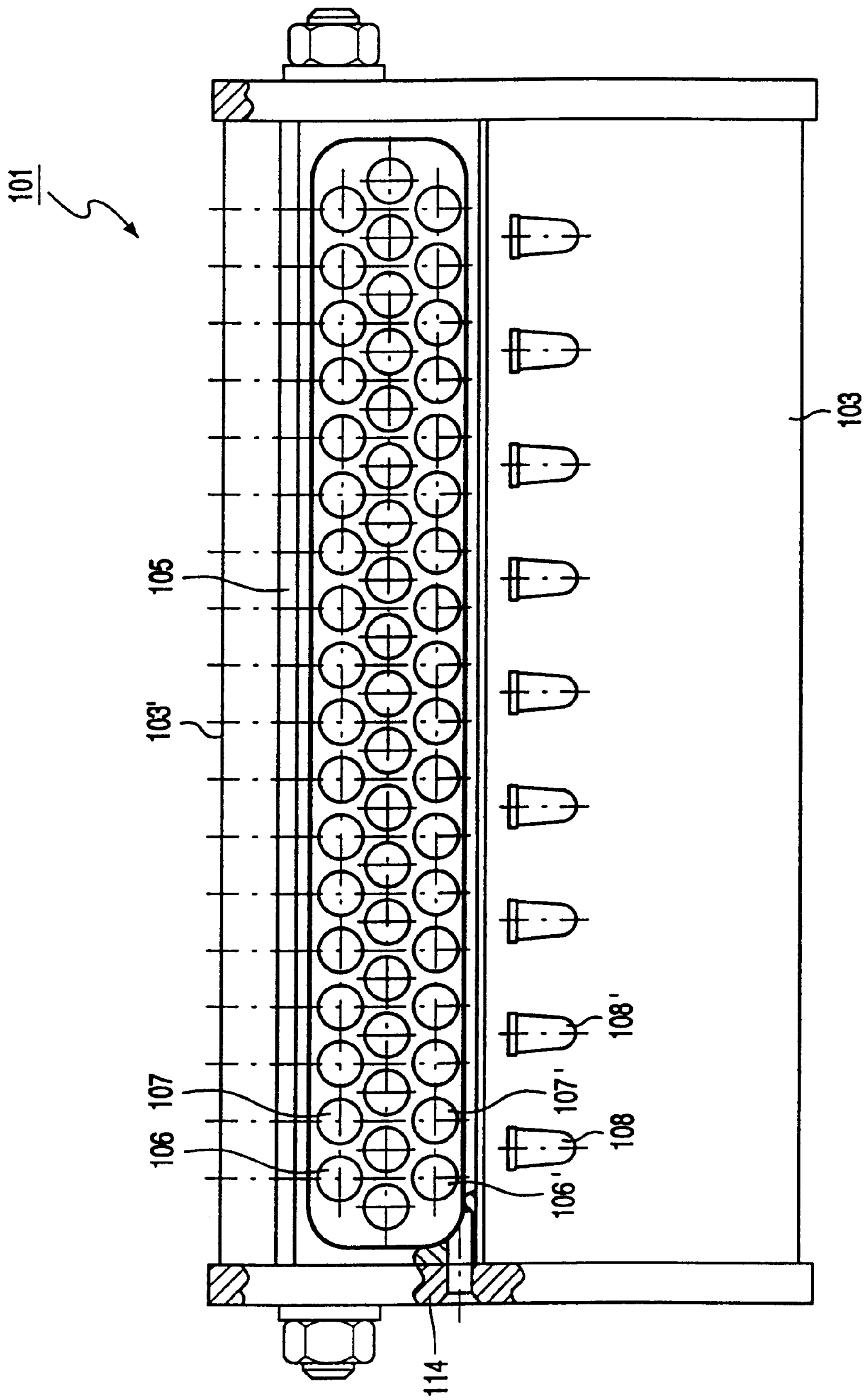


FIG. 3B

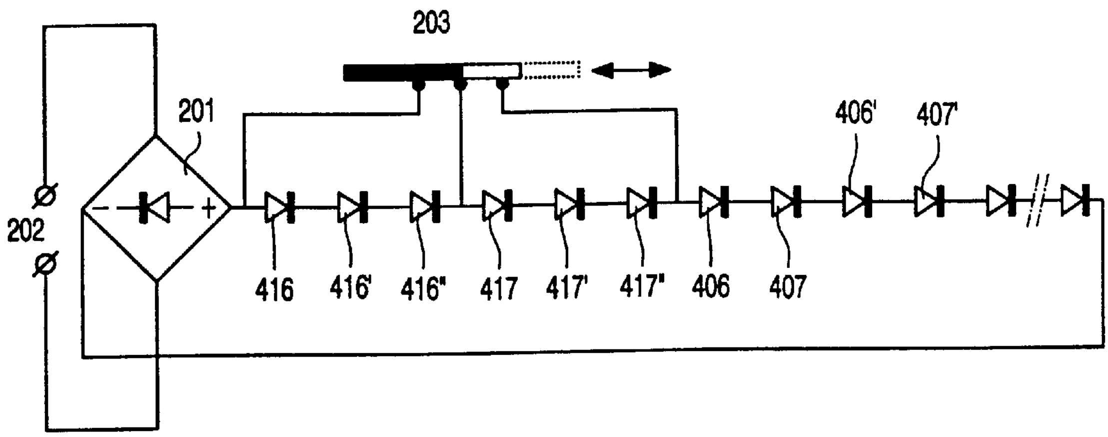

203
201
406'
407'
202
416
416'
416"
417
417'
417"
406
407

FIG. 4

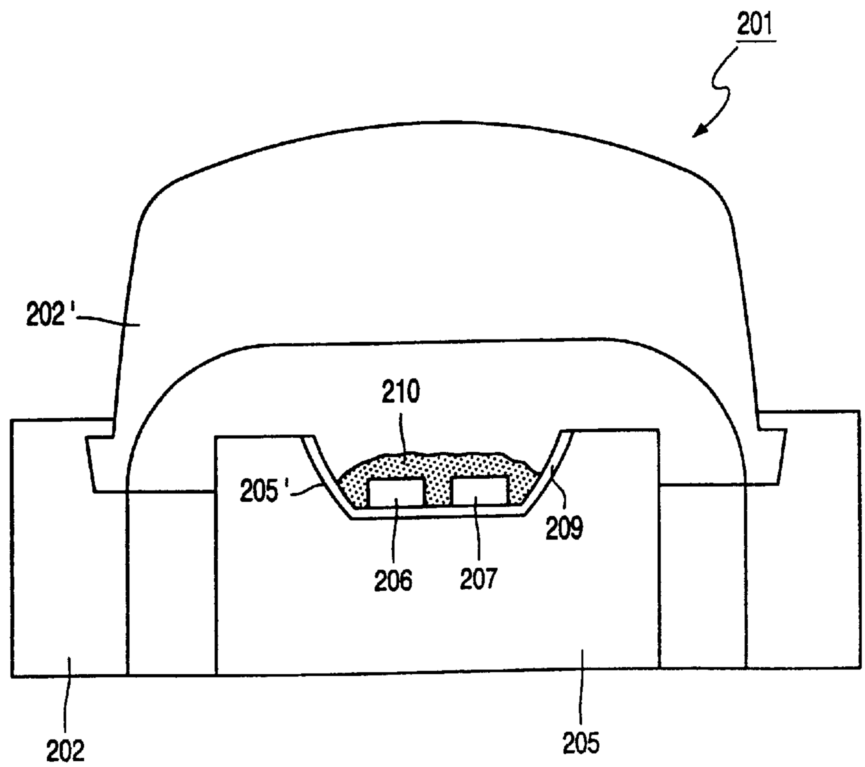

201
202'
210
205'
209
206
207
202
205

FIG. 5

LIGHTING SYSTEM

BACKGROUND OF THE INVENTION

The invention relates to a lighting system comprising at least two light-emitting diodes, each of said light-emitting diodes emitting, in operation, visible light in a preselected wavelength range.

Lighting systems based on light-emitting diodes (LEDs) are used as a source of white light for general lighting applications.

A lighting system of the type mentioned in the opening paragraph is known. In recent years, apart from red light-emitting diodes based on GaP, also efficient, blue light-emitting diodes and green light-emitting diodes based on GaN have been developed. In order to produce white light, in principle, three LEDs are necessary as the primary light source, namely a blue, a green and a red LED.

It is a drawback of such lighting systems that a combination of three LEDs as the primary light source does not always lead to the desired color rendition, which can be attributed to the fact that LEDs with spectral maxima in the desired spectral regions which at the same time are sufficiently energy-efficient are not available or short.

SUMMARY OF THE INVENTION

It is an object of the invention to provide a lighting system, which exhibits an improved color rendition. The invention further aims at improving the luminous efficacy of the lighting system.

To achieve this, the lighting system includes conversion means for converting a part of the visible light emitted by one of the light-emitting diodes into visible light in a further wavelength range so as to optimize the color rendition of the lighting system.

The conversion means are excited by light originating from one of the at least two LEDs. A part of this light is converted by the conversion means, for example via a process of absorption and emission, into visible light in the further wavelength range. This results in a lighting system which comprises, in fact, three light sources, namely two primary light sources which are formed by the at least two LEDs, which primary light sources each emit visible light in a preselected wavelength range, and one so-called secondary light source which emits visible light in the further wavelength range. By a suitable choice of the wavelength ranges in which these two primary light sources and the secondary light source emit visible light, a lighting system is obtained having an improved color rendition relative to a lighting system based on the two primary light sources. Since the application of a third primary light source (for example a green LED or a red LED) is avoided, an improved color rendition of the lighting system is obtained.

Preferably, the conversion means comprise a luminescent material. Such materials are very suitable because they generally have a high quantum efficiency and a high lumen equivalent (expressed in 1m/W), so that a high luminous efficacy of the lighting system is obtained. In addition, many varieties of (stable) inorganic and organic luminescent materials (phosphors) are known, so that the selection of a material for achieving the aim in accordance with the invention (improving the color rendition) is simplified.

The color rendition of the lighting system can be influenced in two ways. On the one hand, the spatial color rendition is improved by optimally mixing the light originating from the LEDs and the conversion means. On the other hand, the color rendition of the lighting system is improved by taking measures which make sure that the light output of the LEDs is independent of time. Such dependence is obtained, for example, if the light output of a LED changes as a function of the temperature of the LED. In this case, the use of temperature-independent LEDs has advantages.

In accordance with a first aspect of the invention, the luminescent material can be preferably excited by light originating from the wavelength range of 400 to 500 nm. By virtue of this sensitivity, the luminescent material can very suitably be used to absorb, in particular, blue light. This absorbed light is very efficiently converted by the luminescent material into visible light in the further wavelength range, for example green light.

Suitable luminescent materials are $(Sr, Ca)_2SiO_4:Eu^{2+}$, $Ba_2SiO_4:Eu^{2+}$, $SrGa_2S_4$, $ZnS:Cu^+$, $ZnS:Au^+$, $ZnS:Al^{3+}$, $(Zn, Cd)S:Ag^+$and $CaS:Ce^{3+}$. Said materials have a relatively high quantum efficiency and light absorption at 450 nm. These materials further exhibit a relatively very high lumen equivalent when blue light is converted to the desired green light.

A very attractive embodiment of the lighting system in accordance with a first aspect of the invention is characterized in that the two light-emitting diodes at least comprise a blue light-emitting diode and at least a red light-emitting diode, and that the conversion means comprise a (green light-emitting) luminescent material for converting a portion of the light emitted by the blue light-emitting diode into green light. In this manner, a lighting system in accordance with a first aspect of the invention is obtained which emits white light with a high color rendering index on the basis of three basic colors (red, blue and green), in which only two primary light sources are employed, namely blue and red light, and green light is obtained by converting a portion of the blue light. Preferably, the maximum of the spectral emission of the blue light-emitting diode lies in the wavelength range from 460 to 490 nm, the maximum of the spectral emission of the red light-emitting diode lies in the wavelength range from 610 to 630 nm, and the maximum of the spectral emission of the (green light-emitting) luminescent material lies in the wavelength range from 510 to 530 nm.

In accordance with a second aspect of the invention, the luminescent material can be preferably excited by light originating from the wavelength range of 500 to 560 nm. By virtue of this sensitivity, the luminescent material can very suitably be used to absorb, in particular, green light. This absorbed light is very efficiently converted by the luminescent material into visible light in the further wavelength range, for example red light.

Suitable luminescent materials are CaS:Eu,Mn; CaS:Eu; SrS:Eu; (Zn,Cd)S:Ag; SrO:Eu; $Sr_3B_2O_6$: Eu; $Sr_2Mg(BO_3)_2$; CaS:Eu, Mn; CaS:Eu or SrS:Eu. Said materials have a relatively high quantum efficiency and light absorption. These materials further exhibit a relatively very high lumen equivalent when blue light or green light is converted to the desired red light.

A very attractive embodiment of the lighting system in accordance with a second aspect of the invention is characterized in that the two light-emitting diodes at least comprise a blue light-emitting diode and at least a green light-emitting diode, and that the conversion means comprise a luminescent material for converting a portion of the light emitted by the blue and/or green light-emitting diode to red light. An important advantage of the use of blue and green LEDs as

the primary light source is that both diode chips can be manufactured by means of the GaN technology known per se. Unlike red GaP diode chips, such blue and green GaN diode chips are not temperature-dependent, so that the use of relatively expensive electronics to compensate for the temperature-dependence of such diode chips can be dispensed with. A further advantage resides in that said blue and green GaN diode chips can be contacted on the same side, so that they can be readily arranged in series. The use of a green-excited luminescent material emitting red light has the additional advantage with respect to a blue-excited luminescent material emitting red light that the quantum deficit is smaller. Preferably, the maximum of the spectral emission of the blue light-emitting diode lies in the wavelength range from 460 to 490 nm, the maximum of the spectral emission of the green light-emitting diode lies in the wavelength range from 510 to 550 nm, and the maximum of the spectral emission of the red light-emitting luminescent material lies in the wavelength range from 610 to 630 nm.

The color rendering index (R_a) of the lighting system in accordance with a first and a second aspect of the invention is preferably at least equal to or greater than 80 ($R_a \geqq 80$). By a suitable combination of the spectral emissions of two primary light sources, which are formed by the at least two LEDs, and the spectral emission of one so-called secondary light source which, after conversion by the conversion means, emits visible light in the further wavelength range, a lighting system having a high color rendering index is obtained.

A point of special interest in the lighting system in accordance with the invention is that upon blending light originating from LEDs with light originating from the conversion means, the direction-dependence of light originating from LEDs (primary light sources) may differ from the direction-dependence of light originating from the conversion means (secondary light source). In general, LEDs emit highly directional light, while the conversion means, in this case the luminescent material, emit (diffuse) light in accordance with a Lambert radiator.

The invention further aims at improving the blending of light by the lighting system. To achieve this, an alternative embodiment of the lighting system in accordance with the invention is characterized in that the lighting system is further provided with reflection means. The LEDs are provided in the lighting system in such a manner that a substantial part of the light originating from the LEDs cannot directly leave the lighting system, but instead is incident on the reflection means. An advantage of the use of reflection means is that the light originating from the two primary light sources (the blue and red LEDs or the blue and green LEDs) and the secondary (green or red) light originating from the conversion means is blended. The reflection means are preferably diffusely reflecting reflection means. By directing the light originating from the LEDs to the diffusely reflecting reflection means, the reflected light also acquires the characteristics of a Lambert radiator. This results in a further improvement of the blending of the various color components and hence of the color rendition of the lighting system. Furthermore, the light is preferably reflected by the reflection means without a change of the color rendition (white-reflecting reflection means). In this manner, undesirable color deviations in the light emitted by the lighting system are precluded. Preferably, the diffusely reflecting reflection means comprise a material chosen from the group formed by $BaSO_4$, ZnS, ZnO and TiO_2. Such materials are very suitable because their reflection coefficient in the wavelength range from 400 to 800 nm is above 98%, and they reflect the light in a diffuse and wavelength-independent manner.

An attractive embodiment of the lighting system in accordance with the invention is characterized in that the conversion means are provided in or on the diffusely reflecting reflection means. In this manner, the light originating from the LEDs is effectively blended, obtains the desired direction characteristic, and the conversion means additionally receive sufficient suitable light for the conversion to visible light in the further wavelength range, which converted light has the same direction characteristic as the diffusely reflected light of the LEDs.

The blending of colors and/or the direction characteristic of the emitted light can be improved in an alternative manner by covering the LEDs with a relatively thin layer of the luminescent material, whereby particles in the luminescent material act as diffusor.

It is further desirable that the color temperature of the lighting system is variable. An alternative embodiment of the lighting system in accordance with the invention is characterized in that the color temperature of the lighting system can be adjusted by separately driving the light-emitting diodes. The color temperature is (electrically) adjustable by separately driving the LEDs. A suitable embodiment of such an adjusting element includes a first diode chain of red and blue LEDs and a second diode chain of exclusively blue (or exclusively red) LEDs. A further suitable embodiment of such an adjusting element includes a first diode chain of blue and green LEDs and a second diode chain of exclusively blue (or exclusively green) LEDs. As a result thereof, an adjustable color temperature range from 2000 to 6300 K is achieved. The color temperature adjustment is partly determined by the quantity of luminescent material (conversion means).

These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a partly cross-sectional view and a side view of an embodiment of the lighting system in accordance with a first aspect of the invention;

FIG. **1**B is a cross-sectional view taken on the line I—I of a detail of the lighting system shown in FIG. **1**A;

FIG. **2** shows the transmission spectrum of an embodiment of the lighting system in accordance with the invention;

FIG. **3**A is a cross-sectional view of an alternative embodiment of the lighting embodiment of the lighting system in accordance with a first aspect of the invention, and

FIG. **3**B is a cross-sectional view of a side view of the alternative embodiment of the lighting system shown in FIG. **3**A;

FIG. **4** is a circuit diagram of LEDs for use in a lighting system in accordance with the invention having an adjustable color temperature, and

FIG. **5** is a cross-sectional view of an embodiment of the lighting system in accordance with a second aspect of the invention.

The Figures are purely schematic and not drawn to scale. Particularly for clarity, some dimensions are exaggerated strongly. In the Figures, like reference numerals refer to like parts, whenever possible.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. **1**A is a partly cross-sectional view and a side view of an embodiment of the lighting system in accordance with

a first aspect of the invention. A lighting system **1** comprises a housing **2** accommodating drive electronics (not shown in FIG. 1A) for the light-emitting diodes (LEDs) and a screen **3**. In this example, the housing is provided with a so-called E27 lamp cap **4** having mechanical and electrical contact means which are known per se. On a side of the lighting system **1** facing away from the lamp cap **4**, there is a holder **5** on which a number of LEDs **6**, **6**', **7**, **7**', **8**, **8**', . . . are provided. The LEDs **6**, **6**', **7**, **7**', comprise a collection of blue LEDs **6**, **6**', (maximum of the spectral emission lies in the wavelength range from 430 to 490 nm) and red LEDs **7**, **7**', (maximum of the spectral emission lies in the wavelength range from 590 to 630 nm), which LEDs **6**, **6**', **7**, **7**', . . . are arranged so that the light that they emit is directed towards the screen **3**. FIG. **1**B very schematically shows an example of a schematic, circular arrangement of the LEDs **6**, **6**', **7**, **7**', (sectioned via the line I—I in FIG. 1A). On a side facing the LEDs **6**, **6**', **7**, **7**' the screen **3** is provided with (diffusely reflecting) reflection means **9** and conversion means **10**. In this example, the reflection means **9** comprise a layer of BaSO4, which material has a (diffuse) reflection coefficient of at least substantially 100% for visible light. The conversion means **10** preferably comprise a luminescent material (phosphor) which bears the characteristic that it converts blue light (400–480 nm) originating from the blue LEDs **6**, **6**', into green light in the desired further wavelength range (530–565 nm). The conversion means **10** convert visible light emitted by one of the light-emitting diodes into visible light in a range having a longer wavelength. A collection of suitable luminescent materials is shown in Table I, where for each of the materials the quantum efficiency at 450 nm (QE_{450}), the absorption coefficient at 450 nm (Abs_{450}) and the lumen equivalent (LE) is indicated.

TABLE I

Luminescent materials (so-called green emitters) which can suitably be used as conversion means for the lighting system in accordance with a first aspect of the invention.

Phosphor	QE_{450} [%]	Abs_{450} [%]	LE[lm/W]
$(Sr,Ca)_2SiO_4:Eu^{2+}$	82	50	430
$Ba_2SiO_4:Eu^{2+}$	64	40	474
$SrGa_2S_4$	90	80	575
$ZnS:Cu^+,Au^+,Al^{3+}$	56	55	505
$(Zn,Cd)S:Ag^+$	>60	100	Dependent upon Zn:Cd ratio
$CaS:Ce^{3+}$	65	80	440

To obtain sufficient green light and to avoid losses, the screen **3** is preferably embodied and arranged so that, dependent upon the degree of reflection of the luminescent material, only one reflection occurs or a number of reflections occur. It is further desirable that the luminescent material at least substantially completely reflects the light of the red LEDs. The light of the red and blue LEDs is effectively blended by the reflection means **9**, the red and blue LEDs **6**, **6**', **7**, **7**', being positioned relative to the screen **3** in such a manner that these LEDs do not directly emit their light in a direction **11** of the light emitted by the lighting system **1**, but that their light output is directed towards an inside of the screen **4** in such a manner that only reflected light is emitted in the direction **11**.

The red and blue LEDs can be separately driven, thus enabling the color temperature of the lighting system **1** to be varied and adjusted in accordance with the requirements. An example hereof is the application of a diode chain with red and blue LEDs and a further diode chain with exclusively blue LEDs (see also FIG. **4**). This ordering of LEDs enables the portion of red light in the primary light source to be varied. Since the ratio of the blue emission relative to the green emission is fixed in such an ordering of LEDs [the blue LEDs **6**, **6**' are directly aimed at the layer with luminescent material ($Ba_2SiO_4:Eu^{2+}$)], the example of FIG. **1**A also contains a number of further blue LEDs **8**, **8**', which emit very diffusely in the direction **11** of the light emitted by the lighting system **1**. This measure enables the red and blue portion in the white light emitted by the lighting system **1** to be separately varied. This results in an additional setting possibility for adjusting the ratio of primary red and blue light and secondary green light, thus providing the lighting system **1** with an adjustable color temperature.

By way of example, Table II shows a lighting system in accordance with a first aspect of the invention, which comprises:

- blue GaN LEDs (make Nichia) with an emission maximum at 470 nm, FWHM=20 nm;
- red GaP LEDs (make Hewlett Packard) with an emission maximum at 620 nm, FWHM=20 nm, two to four blue LEDs being used for each red LED;
- and conversion means comprising a layer of $Ba_2SiO_4:Eu^{2+}$.

Column 1 of Table II lists various desirable values for the color temperature (T_c). The columns 2, 3 and 4 of Table II list the spectral contributions (x) of the three light components (sum of the three spectral contributions x amounts to **1**). Column 5 in Table II lists the color rendering index (R_a) and column 6 lists the luminous efficacy (lum. eff.) of the lighting system. Table II shows that the proportion of green light (column 3) varies relatively little at the different color temperatures. The color temperature of the lighting system can be readily adjusted in a very wide range by only changing the distribution of the primary light sources (the blue and red light).

In accordance with the measure of the invention, a lighting system having a relatively high color rendition ($80 \leqq R_a \leqq 90$) is achieved in this manner.

TABLE II

Combination of blue and red LEDs and $Ba_2SiO_4:Eu^{2+}$ as a luminescent material in an embodiment of the lighting system in accordance with a first aspect of the invention.

T_c [K]	x [blue LED]	x [$Ba_2SiO_4:Eu^{2+}$]	x [red LED]	R_a	lum.eff. [lm/W]
2700	0.069	0.537	0.394	89	21.5
2900	0.108	0.539	0.353	89	22.0
4000	0.186	0.578	0.236	88	22.8
5000	0.251	0.568	0.182	84	23.0
6300	0.302	0.572	0.126	80	23.4

FIG. **2** shows the transmission spectrum of an embodiment of the lighting system in accordance with the invention. The transmission T (arbitrary units) is plotted as a function of the wavelength λ (nm) of visible light for a combination of blue and red LEDs and $Ba_2SiO_4:Eu^{2+}$ as the luminescent material at a color temperature T_c=4000 K (the spectrum in FIG. **2** corresponds to the data in column 4 of Table II). In FIG. **2**, the spectral maximum of the blue LEDs is indicated by (a) and corresponds to a wavelength of 470 nm, and the spectral maximum of the red LEDs is indicated by (b) and corresponds to a wavelength of 620 nm. Furthermore, in FIG. **2**, the spectral maximum of the light emitted by the luminescent material is indicated by (c) and corresponds to a wavelength of 550 nm.

A further improvement of the color rendering index R_a) in accordance with a first aspect of the invention is achieved by not only employing red and blue LEDs as sources of primary light but, for example, a combination of 4 different LEDs. A particularly suitable lighting system in accordance with a first aspect of the invention comprises:

blue GaN LEDs (make Nichia): emission maximum: 470 nm, FWHM=20 nm;

blue-green GaN LEDs (make Nichia): emission maximum: 520 nm, FWHM=40 nm;

yellow GaP LEDs (make Hewlett Packard): emission maximum: 590 nm, FWHM=20 nm;

red GaP LEDs (make Hewlett Packard): emission maximum: 620 nm, FWHM=20 nm;

and conversion means comprising a layer of $Ba_2SiO_4:Eu^{2+}$.

A lighting system having such a combination of four light-emitting diodes and the conversion means in accordance with a first aspect of the invention has a color rendering index which, relative to the various color temperatures listed in Table II, is at least 10 points higher than in the case of a combination of two diodes ($R_a \geqq 90$). Such a lighting system has a luminous efficacy beyond 20 lm/W. For comparison, a typical 100 W incandescent lamp has a luminous efficacy of 14 lm/W (color temperature 2800 K, color rendering index **100**), a 500 W halogen incandescent lamp has a luminous efficacy of approximately 19 lm/W (color temperature 3000 K, color rendering index **100**), while a 36 W fluorescent lamp has a luminous efficacy of approximately 90 lm/W (color temperature 4000 K, color rendering index **85**). A further improvement of the color rendition of the lighting system is achieved by employing deep red LEDs with a spectral emission maximum in the wavelength range from 620 to 670 nm.

FIG. **3**A shows an alternative embodiment of the lighting system in accordance with a first aspect of the invention. FIG. **3**B is a cross-sectional view of a side elevation of the embodiment shown in FIG. **3**A. The lighting system **101** comprises a housing **102** and a screen **103**. This example includes an aperture angle α at which light leaves the lighting system **101** in a direction **111**, which angle can be varied via adjusting screws **113, 113'**. For this purpose, the screen is provided with adjusting plates **114, 114'** having elongated or groove-shaped apertures **115, 115'**. In the example shown in FIG. **3**A, the aperture angle α is equal to 40°. The lighting system **101** comprises a holder **105** on which a number of LEDs **106, 106', 107, 107', 108, 108'**, are provided. The LEDs **106, 106', 107, 107'** include an alternating collection of blue LEDs **106, 106'** (spectral emission $430 \leqq \lambda \leqq 490$ nm) and red LEDs **107, 107'**, . . . (spectral emission $590 \leqq \lambda \leqq 630$ nm), which LEDs **106, 106', 107, 107'** are arranged in such a manner that the light which they emit is directed towards the screen **103** (the direction of the light is schematically indicated by the dotted horizontal light rays in FIG. **3**A). In this example, a part **103'** of the screen **103** comprises an aluminum reflector which may or may not be covered with reflection means, for example a layer of a white pigment, such as $BaSO_4$. Said screen **103** is further provided, on a side facing the LEDs **106, 106', 107, 107'** with a mixture of reflection means **109** ($BaSO_4$) and conversion means **110**, which conversion means preferably include a luminescent material having the property that it converts blue light (400–480 nm) to green light (530–565 nm). A collection of suitable luminescent materials is listed in Table I. The path of the light rays emitted by the LEDs **106, 106', 107, 107'**, and subsequently reflected, is schematically shown in FIG. **3**A by means of dotted lines. The example shown in FIGS. **3**A, **3**B also includes a number of further blue LEDs **108, 108'**, which exhibit a very diffuse emission in the direction **111** of the light emitted by the lighting system **101**.

FIG. **4** shows a circuit diagram of LEDs for use in a lighting system in accordance with the invention having an adjustable color temperature. A voltage is guided from a supply source **202** via a diode bridge **201** to an arrangement of blue LEDs **406, 406'** and red LEDs **407, 407'**. By means of a selector switch **203**, further groups of blue LEDs **416, 416'** and/or red LEDs **417, 417'** can be switched on or off in accordance with the requirements.

FIG. **5** is a cross-sectional view of an embodiment of the lighting system in accordance with a second aspect of the invention. The lighting system **201** comprises a housing **202, 202'**, which accommodates a holder **205** on which a number of LEDs **206;207** are provided. The LEDs **206; 207** include an alternating collection of blue LEDs **206** (spectral emission $430 \leqq \lambda \leqq 490$ nm) and green LEDs **207** (spectral emission $510 \leqq \lambda \leqq 550$ nm), which LEDs **206, 207** are arranged in such a manner that the light which they emit is directed towards an optically transparent part of the housing **202'**. In this example, a part of the holder **205'** comprises a copper reflector which is covered with reflection means **209**, for example a silver layer. In this example, the LEDs are covered with conversion means **210**, which conversion means preferably include a luminescent material having the property that it converts green light (530–565 nm) to red light (610–630 nm). Suitable phosphors which convert blue light to red light are: CaS:Eu, Mn; CaS:Eu; SrS:Eu; (Zn, Cd)S:Ag; SrO:Eu (emission maximum at 625 nm); $Sr_3B_2O_6$:Eu (emission maximum at 590 nm); and $Sr_2Mg(BO_3)_2$ (emission maximum at 605 nm). Suitable phosphors which convert green light to red light are: CaS:Eu, Mn or CaS:Eu (≦550 nm) or SrS:Eu (≦540 nm).

A very suitable lighting system in accordance with a second aspect of the invention comprises:

blue GaN LEDs (make Nichia) with an emission maximum at 470 nm, FWHM=20 nm;

green GaN LEDs (make Nichia) with an emission maximum at 530 nm, FWHM=20 nm;

two or three green LEDs (dependent upon the required color temperature) being used for each blue LED;

and conversion means comprising a layer of CaS:Eu, Mn.

The lighting system in accordance with the invention has the advantage that a high color rendition is achieved ($R_a \geqq 80$) in combination with a relatively high luminous efficacy (≧20 lm/W) and a long service life (≧75,000 hours).

It will be obvious that within the scope of the invention many variations are possible to those skilled in the art.

The scope of protection of the invention is not limited to the examples given in this document. The invention is embodied in each novel characteristic and each combination of characteristics. Reference numerals in the claims do not limit the scope of protection of said claims. The use of the term "comprising" does not exclude the presence of elements other than those mentioned in the claims. The use of the term "a" or "an" in front of an element does not exclude the presence of a plurality of such elements.

What is claimed is:

1. A lighting system comprising at least two light-emitting diodes, each of said at least two light-emitting diodes emitting, in operation, visible light in a preselected wavelength range, and

conversion means for converting a part of the visible light emitted by one of the at least two light-emitting diodes

into visible light in a further wavelength range so as to optimize the color rendition of the lighting system;

wherein the at least two light-emitting diodes comprise at least a blue light-emitting diode and at least a red light-emitting diode; and

wherein the conversion means include a luminescent material for converting a portion of the light emitted by the blue light-emitting diode into green light.

2. A lighting system as claimed in claim **1**, wherein the luminescent material can be excited by light originating from one of a wavelength range from 400 to 500 nm and another wavelength range from 500 to 560 nm.

3. A lighting system as claimed in claim **1**, wherein the luminescent material is chosen from one of a group formed by $(Sr,Ca)_2SiO_4:Eu^{2+}$, $Ba_2SiO_4:Eu^{2+}$, $SrGa_2S_4$, $ZnS:Cu^+$, $ZnS:Au^+$, $ZnS:Al^{3+}$, $(Zn,Cd)S:Ag^+$ and $CaS:Ce^{3+}$, and another group formed by CaS:Eu,Mn; CaS:Eu; SrS:Eu; (Zn, Cd)S:Ag; SrO:Eu; $Sr_3B_2O_6:Eu$; $Sr_2Mg(BO_3)_2$; CaS:Eu, Mn; CaS:Eu or SrS:Eu.

4. A lighting system comprising at least two light-emitting diodes, each of said at least two light-emitting diodes emitting, in operation, visible light in a preselected wavelength range, and

conversion means for converting a part of the visible light emitted by one of the at least two light-emitting diodes into visible light in a further wavelength range so as to optimize the color rendition of the lighting system;

wherein the at least two light-emitting diodes at least comprise a blue light-emitting diode and at least a green light-emitting diode, and wherein the conversion means comprise a luminescent material for converting a portion of the light emitted by at least one of the blue and green light-emitting diodes to red light.

5. A lighting system as claimed in claim **1**, wherein a color rendering index of the lighting system is at least equal to or greater than 80.

6. A lighting system as claimed in claim **1** wherein, in operation, each of the at least two light-emitting diodes has a luminous flux of at least 5 lm.

7. A lighting system comprising at least two light-emitting diodes, each of said at least two light-emitting diodes emitting, in operation, visible light in a preselected wavelength range;

conversion means for converting a part of the visible light emitted by one of the at least two light-emitting diodes into visible light in a further wavelength range so as to optimize the color rendition of the lighting system; and

reflection means.

8. A lighting system as claimed in claim **7**, wherein the reflection means comprise a material chosen from the group formed by $BaSO_4$, ZnS, ZnO and TiO_2.

9. A lighting system as claimed in claim **7**, wherein the conversion means are provided in or on the reflection means.

10. A lighting system comprising at least two light-emitting diodes, each of said at least two light-emitting diodes emitting, in operation, visible light in a preselected wavelength range;

conversion means for converting a part of the visible light emitted by one of the at least two light-emitting diodes into visible light in a further wavelength range so as to optimize the color rendition of the lighting system; and

means for separately driving the at least two light-emitting diodes.

11. A lighting system as claimed in claim **7**, wherein the conversion means comprise a luminescent material.

12. A lighting system as claimed in claim **11**, wherein the luminescent material can be excited by light originating from one of a wavelength range from 400 to 500 nm and another wavelength range from 500 to 560 nm.

13. A lighting system as claimed in claim **11**, wherein the luminescent material is chosen from one of a group formed by $(Sr,Ca)_2SiO_4:Eu^{2+}$, $Ba_2SiO_4:Eu^{2+}$, $SrGa_2S_4$, $ZnS:Cu^+$, $ZnS:Au^+$, $ZnS:Al^{3+}$, $(Zn,Cd)S:Ag^+$ and $CaS:Ce^{3+}$, and another group formed by CaS:Eu,Mn; CaS:Eu; SrS:Eu; (Zn, Cd)S:Ag; SrO:Eu; $Sr_3B_2O_6:Eu$; $Sr_2Mg(BO_3)_2$; CaS:Eu, Mn; CaS:Eu or SrS:Eu.

14. A lighting system as claimed in claim **7**, wherein a color rendering index of the lighting system is at least equal to or greater than 80.

15. A lighting system as claimed in claim **7** wherein, in operation, each of the at least two light-emitting diodes has a luminous flux of at least 5 lm.

16. A lighting system as claimed in claim **10**, wherein the conversion means comprise a luminescent material.

17. A lighting system as claimed in claim **16**, wherein the luminescent material can be excited by light originating from one of a wavelength range from 400 to 500 nm and another wavelength range from 500 to 560 nm.

18. A lighting system as claimed in claim **16**, wherein the luminescent material is chosen from one of a group formed by $(Sr,Ca)_2SiO_4:Eu^{2+}$, $Ba_2SiO_4:Eu^{2+}$, $SrGa_2S_4$, $ZnS:Cu^+$, $ZnS:Au^+$, $ZnS:Al^{3+}$, $(Zn,Cd)S:Ag^+$ and $CaS:Ce^{3+}$, and another group formed by CaS:Eu,Mn; CaS:Eu; SrS:Eu; (Zn, Cd)S:Ag; SrO:Eu; $Sr_3B_2O_6:Eu$; $Sr_2Mg(BO_3)_2$; CaS:Eu, Mn; CaS:Eu or SrS:Eu.

19. A lighting system as claimed in claim **10**, wherein a color rendering index of the lighting system is at least equal to or greater than 80.

20. A lighting system as claimed in claim **10** wherein, in operation, each of the at least two light-emitting diodes has a luminous flux of at least 5 lm.

* * * * *

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Marshall et al.

(10) **Patent No.: US 6,513,949 B1**
(45) **Date of Patent: Feb. 4, 2003**

(54) **LED/PHOSPHOR-LED HYBRID LIGHTING SYSTEMS**

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(51) **Int. Cl.**^{7} **F21V 9/00**
(52) **U.S. Cl.** **362/231**; 362/800; 313/502
(58) **Field of Search** 362/231, 293, 362/800, 230, 228, 242, 84; 257/98, 99, 100, 89; 313/502, 503, 504

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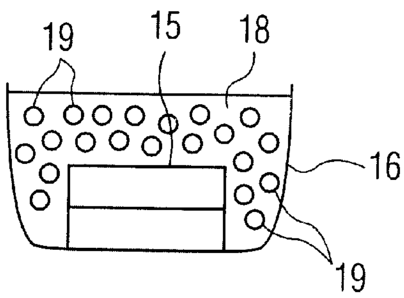
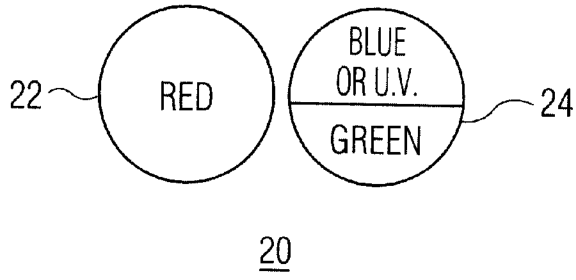
Primary Examiner—Sandra O'Shea
Assistant Examiner—Bao Truong

(57) **ABSTRACT**

A hybrid lighting system for producing white light including at least one light emitting diode and phosphor-light emitting diode. The hybrid lighting system exhibits improved performance over conventional LED lighting systems that use LEDs or phosphor-LEDs to produce white light. In particular, the hybrid system of the invention permits different lighting system performance parameters to be addressed and optimized as deemed important, by varying the color and number of the LEDs and/or the phosphor of the phosphor LED.

12 Claims, 3 Drawing Sheets





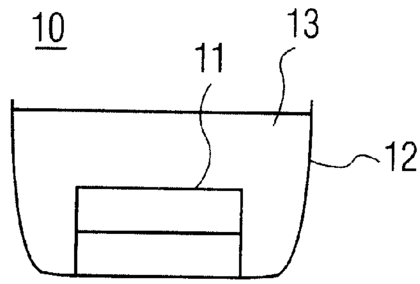


FIG. 1a

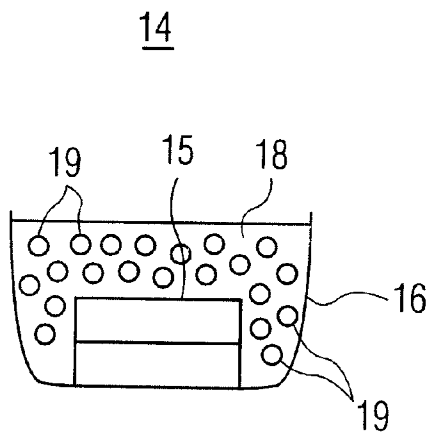


FIG. 1b

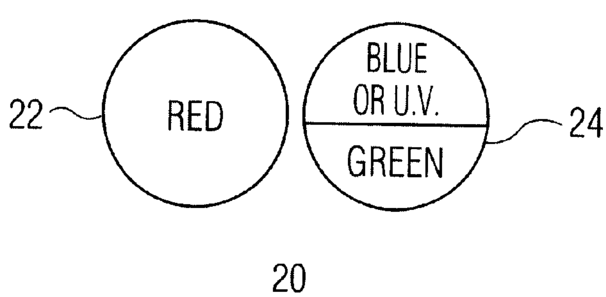


FIG. 2

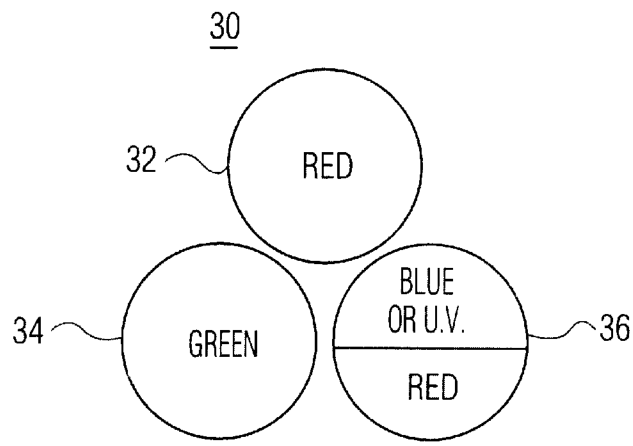


FIG. 3

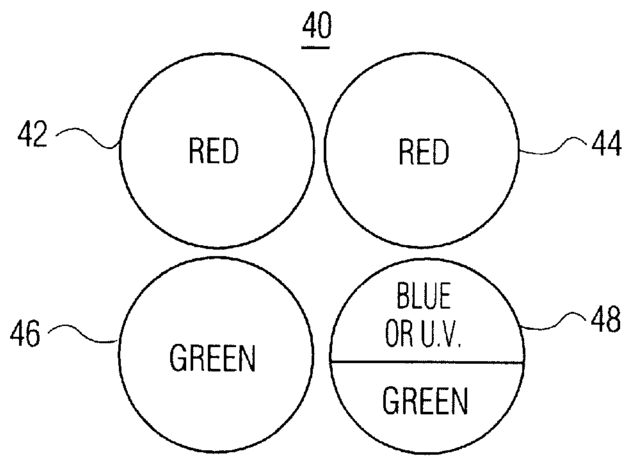


FIG. 4

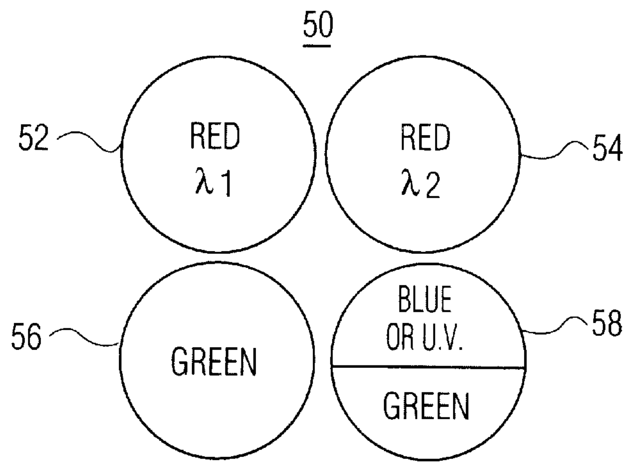


FIG. 5

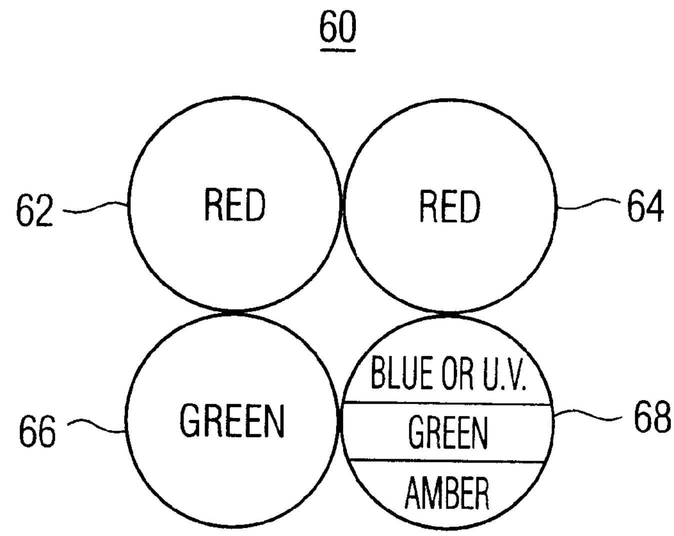

60
62
RED
RED
64
66
GREEN
BLUE OR U.V.
GREEN
AMBER
68

FIG. 6

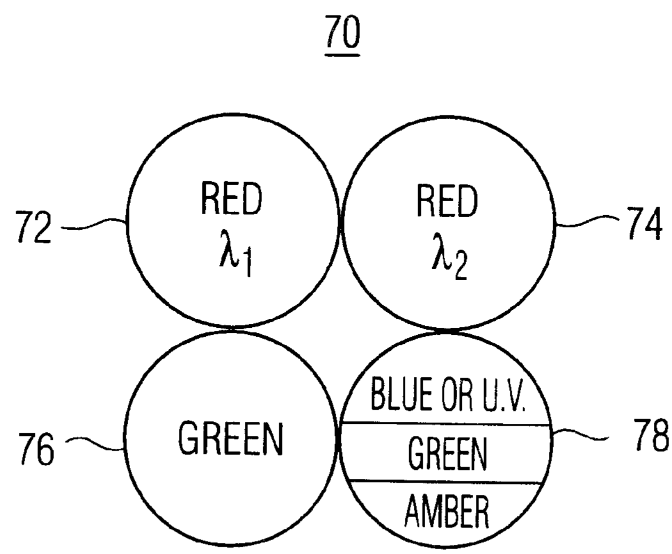

70
72
RED
λ_1
RED
λ_2
74
76
GREEN
BLUE OR U.V.
GREEN
AMBER
78

FIG. 7

LED/PHOSPHOR-LED HYBRID LIGHTING SYSTEMS

FIELD OF THE INVENTION

This invention relates to light emitting diode (LED) lighting systems for producing white light, and in particular to hybrid LED lighting systems for producing white light comprised of LEDs and phosphor-LEDs. The hybrid lighting system exhibits improved performance over conventional LED lighting systems that use LEDs or phosphor-LEDs to produce white light.

BACKGROUND AND SUMMARY OF THE INVENTION

Conventional LED lighting systems for producing white light typically comprise either LEDs or phosphor-LEDs. Lighting systems which use LEDs produce white light by combining various combinations of red, green, and blue LEDs. Phosphor-LED based lighting systems produce white light by using one or more various luminescent phosphor materials on top of a blue light LED to convert a portion of the emitted blue light into light of a longer wavelength.

Lighting systems which use LEDs to produce white light are more efficient at the package level than lighting systems which use phosphor-LEDs. However, high quality white light is more difficult to achieve in LED based lighting systems. This is because LEDs manufactured to optimize total lighting system performance and production typically must be combined in an undesirably large integral number of LED chips to provide the requisite quantities of red, green and blue light when operated at full rated power. Moreover, the LED chips must be fabricated in different sizes to achieve the proper balance thus, increasing the production costs of the system. Since the green and blue LED chips are manufactured in the same AlInGaN technology, there are fabrication and cost advantages to making these chips the same size, and reasonably large.

There are other limitations associated with LED based lighting systems. Existing green LEDs operating at the very desirable light spectral wavelength of about 550 nm are very inefficient. The highest luminous-efficacy green LED operates at a less desirable light spectral wavelength of about 530 nm. Further, currently available efficient LEDs make good color rendering difficult to achieve. Good color rendering is possible, but places constraints on specific choices of LEDs.

Additionally, mixing LEDs to produce white light entails material and particularly efficiency costs. More specifically, many highly collimated mixing schemes are binary in that they mix two LEDs at a time. LED based lighting systems typically use three and four LEDs and thus, require two stages of mixing. Unfortunately, each stage of mixing has an efficiency cost which significantly lowers the performance of the system.

As alluded to earlier, it is easier to produce white light with phosphor-LED based lighting systems as compared with LED based lighting systems because phosphor-LEDs do not require mixing and have lower material costs (they are inherently mixed). However, they are less efficient by a factor of about two at the package level than LED based lighting systems because of quantum deficits and re-emission efficiencies.

Accordingly, there is a need for a lighting system which combines certain aspects of LED and phosphor-LED based lighting systems to achieve benefits beyond either system.

Accordingly, we disclose herein a lighting system for producing white light that includes at least one LED and a phosphor-LED disposed adjacent to the at least one LED.

BRIEF DESCRIPTION OF THE DRAWINGS

The advantages, nature, and various additional features of the invention will appear more fully upon consideration of the illustrative embodiments now to be described in detail in connection with accompanying drawings wherein:

FIG. **1**A is a sectional view of a typical LED used in the lighting system of the invention;

FIG. **1**B is a sectional view of a typical phosphor-LED used in the lighting system of the invention;

FIG. **2** is a schematic diagram depicting a first embodiment of the lighting system of the invention;

FIG. **3** is a schematic diagram depicting a second embodiment of the lighting system of the invention

FIG. **4** is a schematic diagram depicting a third embodiment of the lighting system of the invention;

FIG. **5** is a schematic diagram depicting a fourth embodiment of the lighting system of the invention;

FIG. **6** is a schematic diagram depicting a fifth embodiment of the lighting system of the invention; and

FIG. **7** is a schematic diagram depicting a sixth embodiment of the lighting system of the invention.

It should be understood that these drawings are for purposes of illustrating the concepts of the invention and are not to scale.

DETAILED DESCRIPTION OF THE INVENTION

The hybrid lighting system of the invention generally comprises selectively combining one or more certain LEDs with a phosphor-LED consisting of a blue LED and at least one phosphor which emits at certain light spectral wavelength (color), to produce white light.

FIG. **1**A schematically depicts a typical LED **10** used in the invention. The LED **10** is conventionally constructed using standard AlInGaN or AlInGaP processing and comprises an LED chip **11** mounted in a reflective metal dish or reflector **12** filled with a transparent epoxy **13**.

FIG. **1**B schematically depicts a typical phosphor-LED **14** used in the invention. This LED **14** is substantially identical in construction to the LED of FIG. **1**A, except that the epoxy **18** filling the reflector **16** contains grains **19** of one or more types of luminescent phosphor materials mixed homogeneously therein. The phosphor grains **19** convert a portion of the light emitted by the LED chip **15** to light of a different spectral wavelength.

A primary advantage of the hybrid system of the invention is that it permits different lighting system performance parameters to be addressed and optimized as deemed important by varying the color and number of the LEDs and/or the phosphor of the phosphor-LED. In particular, the system of the present invention can address and achieve higher available lumens-per-chip averages via balancing red and green and blue light components; smaller integral numbers of LEDs at balance; improved color rendering; and more efficient mixing via the phosphor-LED. This in turn advantageously permits the manufacture of various types of products which are optimized for various applications using LED chips manufactured with standard AlInGaN and AlInGaP processing.

Each of the following embodiments illustrate how one or more of the above performance advantages can be achieved

using the hybrid system of the invention. FIG. **2** schematically depicts a first embodiment of the hybrid lighting system of the invention denoted by numeral **20**. The system **20** comprises a red LED **22** that emits light having a spectral wavelength of about 610 nm and a phosphor-LED **24** consisting of a blue LED that emits light having a spectral wavelength of between about 450 nm and 470 nm, and a phosphor material that converts a portion (typically about 50%) of the blue light to green light having a spectral wavelength of about 550 nm. This embodiment of the inventive system provides reasonable power balance and achieves an overall system efficiency comparable with or exceeding conventional LED based lighting systems because it eliminates the need for a less efficient green LED (typically emits light having a spectral wavelength of about 530 nm) as employed in conventional LED based lighting systems (the phosphor LED could be fundamentally more efficient than the green LED chip because it has better access to the 550 nm range and thus, has a lumen-per-watt advantage). Moreover, the two LEDs **22**, **24** of this embodiment of the system **20** are easier and more efficient to mix, and require less complex LED drive electronics than conventional lighting systems which typically employ three or four LEDs. More specifically, there are many mixing schemes for mixing LEDs. In virtually all of these schemes, less mixing is desirable. For example, in binary mixing schemes, only one mixing stage is required to mix the two LEDs **22**, **24** of the inventive system **20** compared with two mixing stages required for conventional LED based lighting systems. Hence, approximately half the mixing losses of conventional LED based lighting systems are incurred with this embodiment of the system. Therefore, significantly higher overall system efficiency can be realized in this embodiment of the system when compared with conventional LED based lighting systems. Color rendering is adequate owing to the 550 nm light provided by the phosphor-LED **24** although the color point can only be adjusted along a line. Consequently, control over color temperature is only possible at the design point. However, such an embodiment of the invention is especially useful for producing a fixed white light in lower cost lighting system applications where less expensive LED drive electronics are desirable and truly versatile control over color temperature is not significantly important.

FIG. **3** schematically depicts a second embodiment of the hybrid lighting system of the invention denoted by numeral **30**. The system **30** comprises a red LED **32** (emits light having a spectral wavelength of about 610 nm), a green LED **34** (emits light having a spectral wavelength of about 530 nm) and a phosphor-LED **36** consisting of a blue LED (emits between ~450 nm and ~470 nm) and a phosphor material that converts a portion (about 50%) of the emitted blue light to red light (about 610 nm). In comparison to conventional LED based systems which typically produce insufficient quantities of red light and excessive quantities of blue light, the phosphor LED **36** used in this embodiment of the inventive system balances the deficiency in red light output and attenuates the blue light output thereby providing good color balance with only three LEDs. Color rendering and color-temperature control is comparable to conventional LED based lighting systems. In particular, the use of three LEDs can provide maximum lumen content while permitting the color temperature to be freely adjusted, since the red content of the phosphor-LED **36** is sufficiently small to allow a balance to be struck by merely raising and lowering the brightness of the three LEDs via adjustments in the drive currents.

FIG. **4** schematically depicts a third embodiment of the hybrid lighting system of the invention denoted by numeral **40**. The system **40** comprises two red LEDs **42**, **44** (emits at ~610 nm), a green LED **46** (emits at ~530 nm), and a phosphor-LED **48** consisting of a blue LED (emits between ~450 nm and ~470 nm) and a phosphor material that converts a portion of the blue light to green light having a spectral wavelength of about 550 nm. Since the phosphor has a power conversion efficiency of about 50%, sufficient quantities of blue and green light are generated by the phosphor-LED **48** thereby providing excellent balance and color rendering at the design point owing to the presence of the 550 nm light. Additionally, the 550 nm light produces much greater lumen content, thereby providing this embodiment of the system with a higher lumen output, even when the phosphor's conversion energy loss if factored in.

FIG. **5** schematically depicts a fourth embodiment of the hybrid lighting system of the invention denoted by numeral **50**. The system **50** is substantially identical to the system of the third embodiment in that it comprises two red LEDs **52**, **54**, a green LED **56** and a phosphor-LED **58** that emits blue light and green light. However, the two red LEDs **52**, **54** emit light at two slightly different spectral wavelengths (~610 nm and ~595 nm). The red LED emitting at about 595 nm produces a red color that is orange-amberlike to provide further improvements in color rendering.

FIG. **6** schematically depicts a fifth embodiment of the hybrid lighting system of the invention denoted by numeral **60**. The system **60** is substantially identical to the system of the third embodiment in that it comprises two red LEDs **62**, **64**, a green LED **56** and a phosphor-LED **68**. However, the phosphor-LED **68** consists of a blue LED with a first phosphor material that emits at a light spectral wavelength of about 550 nm to convert a portion of the blue light to green light and a second phosphor material that converts a portion of the remaining blue light not converted by the first phosphor to an amber or yellow-green light. This embodiment exhibits further improvements in color rendering and is therefore useful in applications requiring maximized color rendering.

FIG. **7** schematically depicts a sixth embodiment of the hybrid lighting system of the invention denoted by numeral **70**. The system **70** combines the features of the fourth and fifth embodiments and thus, comprises a first red LED **72** (emits at ~610 nm), a second red LED **74** (emits at ~595 nm), a green LED (emits at ~530 nm) **76**, and a phosphor-LED **78**. The phosphor LED consists of a blue LED (emits between ~450 nm and ~470 nm) and a first phosphor material that emits at a light spectral wavelength of about 550 nm to convert a portion of the blue light to green light and a second phosphor material that converts a portion of the remaining blue light not converted by the first phosphor, to an amber or yellow-green light. This embodiment is also especially useful in applications requiring optimized color rendering.

While the foregoing invention has been described with reference to the above embodiments, various modifications and changes can be made without departing from the spirit of the invention. Accordingly, all such modifications and changes are considered to be within the scope of the appended claims.

What is claimed is:

1. A lighting system for producing white light, the system comprising:

at least one light emitting diode that emits red light; and

a phosphor-light emitting diode disposed adjacent to the at least one light emitting diode,

wherein the phosphor-light emitting diode emits light of at least a third different color, the color being selected from the group consisting of amber and yellow-green.

2. The lighting system of claim **1**, further comprising at least a second light emitting diode which emits green light and a third light emitting diode which emits red light,

wherein the phosphor-light emitting diode includes a blue light emitting diode that emits blue light and at least one phosphor that converts at least a portion of the blue light to one of a green light and a red light.

3. The lighting system of claim **2**, wherein the spectral wavelength of the red light emitted from the first light emitting diode is different from the spectral wavelength of the red light emitted from the third light emitting diode.

4. The lighting system of claim **1**, wherein the phosphor-light emitting diode includes a blue light emitting diode that emits blue light and at least one phosphor that converts at least a portion of the blue light to one of a green light and a red light.

5. A lighting system for producing white light, the system comprising:

at least one light emitting diode; and

a phosphor-light emitting diode that emits at least two different colors of light, disposed adjacent to the at least one light emitting diode,

wherein the phosphor-light emitting diode emits at least three different colors of light, one of which three different colors is selected from the group consisting of amber and yellow-green.

6. A lighting system for producing white light, the system comprising:

at least two light emitting diodes; and

a phosphor-light emitting diode disposed adjacent to the at least one light emitting diode,

wherein the phosphor-light emitting diode emits at least three different colors of light, one of which three different colors is selected from the group consisting of amber and yellow-green.

7. The lighting system of claim **6**, wherein the phosphor-light emitting diode emits at least two different colors of light, one of the at least two colors being at least substantially identical to the color emitted by at least one of the light emitting diodes.

8. The lighting system of claim **6**, wherein the light emitted from the light emitting diodes are of the same general color but have different spectral wavelengths.

9. The lighting system of claim **6**, further comprising at least a third light emitting diode.

10. The lighting system of claim **9**, wherein the light emitted from two of the three light emitting diodes are of the same general color but have different spectral wavelengths.

11. The lighting system of claim **1**, further comprising at least a second light emitting diode which emits green light, wherein the phosphor-light emitting diode includes a blue light emitting diode that emits blue light and at least one phosphor that converts at least a portion of the blue light to one of a green light and a red light.

12. The lighting system of claim **1**, further comprising at least a second light emitting diode which emits green light.

* * * * *

US006692136B2

(12) **United States Patent**
Marshall et al.

(10) **Patent No.:** **US 6,692,136 B2**
(45) **Date of Patent:** ***Feb. 17, 2004**

(54) **LED/PHOSPHOR-LED HYBRID LIGHTING SYSTEMS**

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(73) Assignee: **Koninklijke Philips Electronics N.V.**, Eindhoven (NL)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **10/302,315**

(22) Filed: **Nov. 22, 2002**

(65) **Prior Publication Data**

US 2003/0067773 A1 Apr. 10, 2003

Related U.S. Application Data

(63) Continuation of application No. 09/453,420, filed on Dec. 2, 1999, now Pat. No. 6,513,949.

(51) **Int. Cl.**^{7} **F21V 9/00**

(52) **U.S. Cl.** **362/231**; 362/230; 362/800

(58) **Field of Search** 362/228, 230, 362/231, 242, 293, 800, 84; 257/98, 99, 89, 100; 313/502, 503, 504

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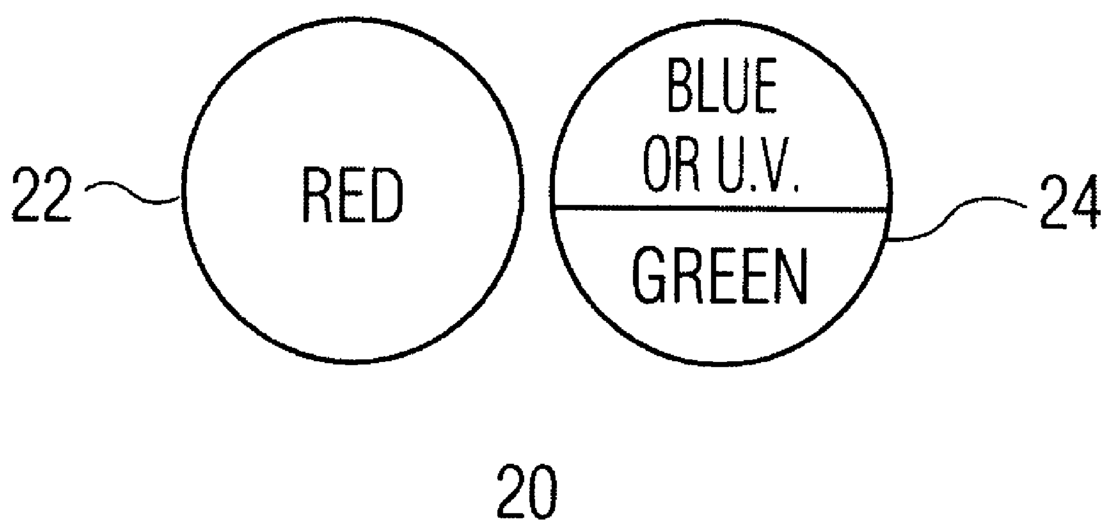
Primary Examiner—Alan Cariaso
Assistant Examiner—Bao Q. Truong

(57) **ABSTRACT**

A hybrid lighting system for producing white light including at least one light emitting diode and phosphor-light emitting diode. The hybrid lighting system exhibits improved performance over conventional LED lighting systems that use LEDs or phosphor-LEDs to produce white light. In particular, the hybrid system of the invention permits different lighting system performance parameters to be addressed and optimized as deemed important, by varying the color and number of the LEDs and/or the phosphor of the phosphor LED.

16 Claims, 3 Drawing Sheets



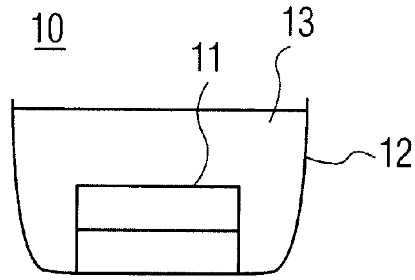


FIG. 1a

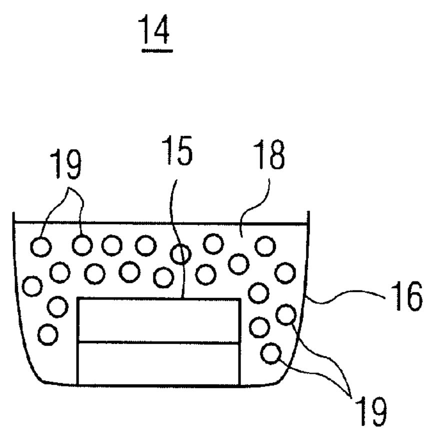


FIG. 1b

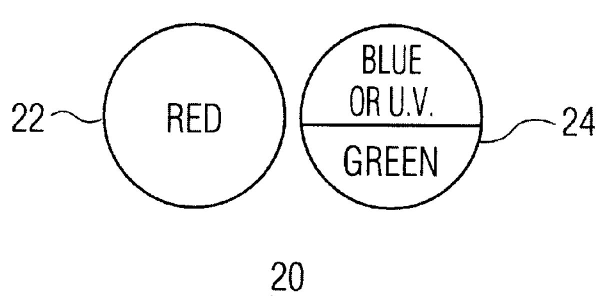


FIG. 2

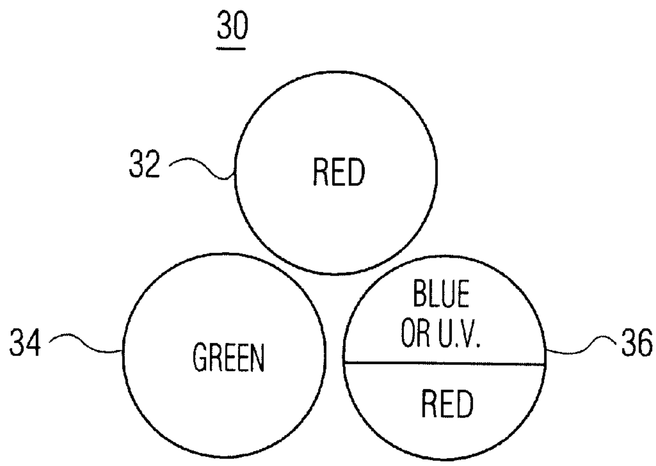


FIG. 3

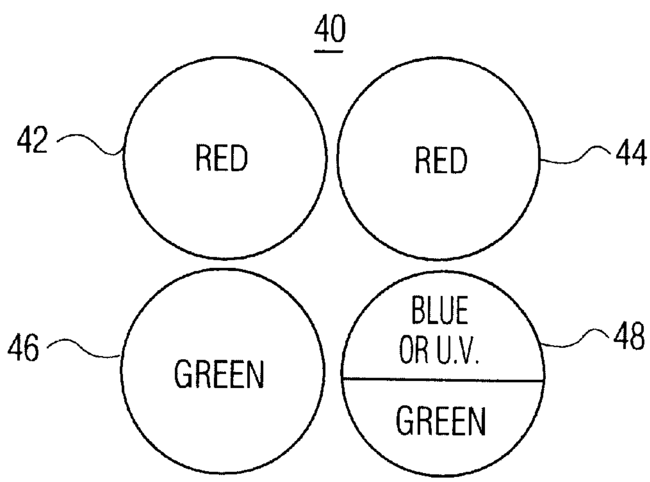


FIG. 4

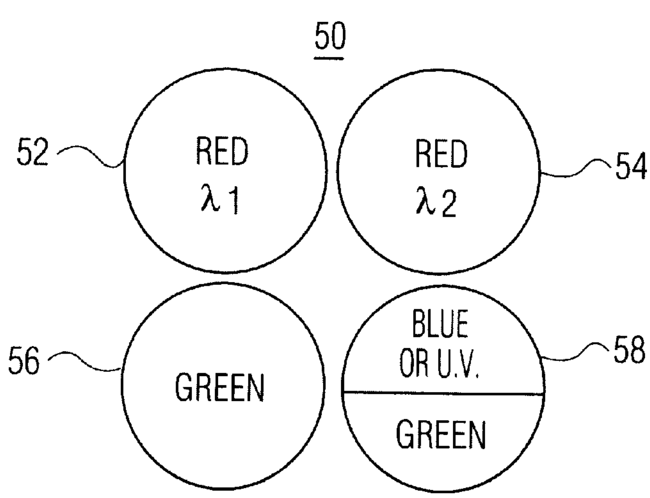


FIG. 5

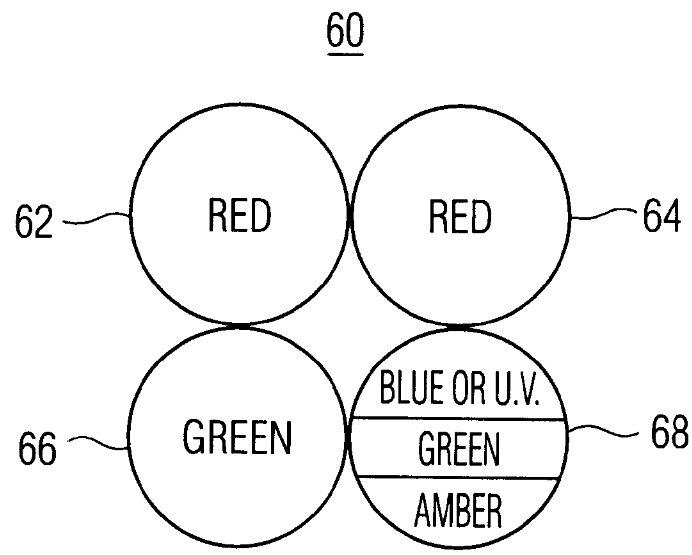

60
RED
RED
62
64
GREEN
BLUE OR U.V.
GREEN
AMBER
66
68

FIG. 6

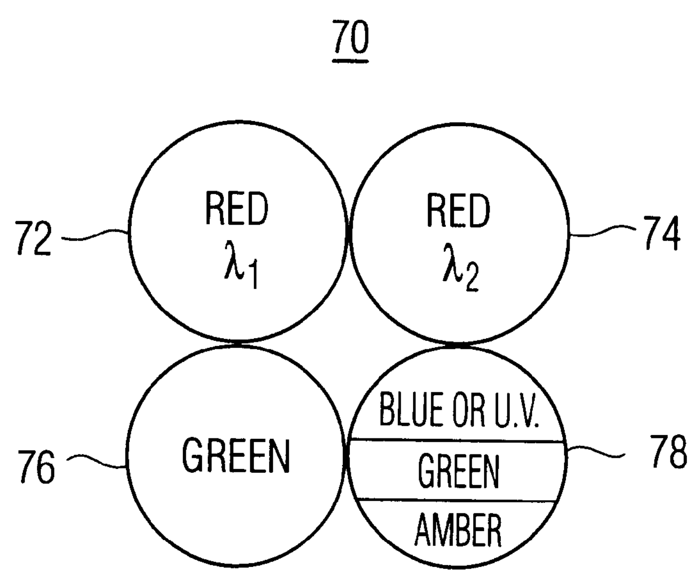

70
RED
λ_1
RED
λ_2
72
74
GREEN
BLUE OR U.V.
GREEN
AMBER
76
78

FIG. 7

LED/PHOSPHOR-LED HYBRID LIGHTING SYSTEMS

CROSS REFERENCE TO RELATED APPLICATIONS

This is a continuation of application Ser. No. 09/453,420, filed Dec. 2, 1999 now U.S. Pat. No. 6,513,949.

FIELD OF THE INVENTION

This invention relates to light emitting diode (LED) lighting systems for producing white light, and in particular to hybrid LED lighting systems for producing white light comprised of LEDs and phosphor-LEDs. The hybrid lighting system exhibits improved performance over conventional LED lighting systems that use LEDs or phosphor-LEDs to produce white light.

BACKGROUND AND SUMMARY

Conventional LED lighting systems for producing white light typically comprise either LEDs or phosphor-LEDs. Lighting systems which use LEDs produce white light by combining various combinations of red, green, and blue LEDs. Phosphor-LED based lighting systems produce white light by using one or more various luminescent phosphor materials on top of a blue light LED to convert a portion of the emitted blue light into light of a longer wavelength.

Lighting systems which use LEDs to produce white light are more efficient at the package level than lighting systems which use phosphor-LEDs. However, high quality white light is more difficult to achieve in LED based lighting systems. This is because LEDs manufactured to optimize total lighting system performance and production typically must be combined in an undesirably large integral number of LED chips to provide the requisite quantities of red, green and blue light when operated at full rated power. Moreover, the LED chips must be fabricated in different sizes to achieve the proper balance thus, increasing the production costs of the system. Since the green and blue LED chips are manufactured in the same AlInGaN technology, there are fabrication and cost advantages to making these chips the same size, and reasonably large.

There are other limitations associated with LED based lighting systems. Existing green LEDs operating at the very desirable light spectral wavelength of about 550 nm are very inefficient. The highest luminous-efficacy green LED operates at a less desirable light spectral wavelength of about 530 nm. Further, currently available efficient LEDs make good color rendering difficult to achieve. Good color rendering is possible, but places constraints on specific choices of LEDs.

Additionally, mixing LEDs to produce white light entails material and particularly efficiency costs. More specifically, many highly collimated mixing schemes are binary in that they mix two LEDs at a time. LED based lighting systems typically use three and four LEDs and thus, require two stages of mixing. Unfortunately, each stage of mixing has an efficiency cost which significantly lowers the performance of the system.

As alluded to earlier, it is easier to produce white light with phosphor-LED based lighting systems as compared with LED based lighting systems because phosphor-LEDs do not require mixing and have lower material costs (they are inherently mixed). However, they are less efficient by a factor of about two at the package level than LED based lighting systems because of quantum deficits and re-emission efficiencies.

Accordingly, there is a need for a lighting system which combines certain aspects of LED and phosphor-LED based lighting systems to achieve benefits beyond either system.

Accordingly, a lighting system for producing white light is disclosed that includes at least one LED and a phosphor LED disposed adjacent to the at least one LED.

BRIEF DESCRIPTION OF THE DRAWINGS

The advantages, nature, and various additional features of the invention will appear more fully upon consideration of the illustrative embodiments now to be described in detail in connection with accompanying drawings wherein:

FIG. **1**A is a sectional view of a typical LED used in the lighting system of the invention;

FIG. **1**B is a sectional view of a typical phosphor-LED used in the lighting system of the invention;

FIG. **2** is a schematic diagram depicting a first embodiment of the lighting system of the invention;

FIG. **3** is a schematic diagram depicting a second embodiment of the lighting system of the invention

FIG. **4** is a schematic diagram depicting a third embodiment of the lighting system of the invention;

FIG. **5** is a schematic diagram depicting a fourth embodiment of the lighting system of the invention;

FIG. **6** is a schematic diagram depicting a fifth embodiment of the lighting system of the invention; and

FIG. **7** is a schematic diagram depicting a sixth embodiment of the lighting system of the invention.

It should be understood that these drawings are for purposes of illustrating the concepts of the invention and are not to scale.

DETAILED DESCRIPTION OF THE INVENTION

The hybrid lighting system of the invention generally comprises selectively combining one or more certain LEDs with a phosphor-LED consisting of a blue LED and at least one phosphor which emits at certain light spectral wavelength (color), to produce white light.

FIG. **1**A schematically depicts a typical LED **10** used in the invention. The LED **10** is conventionally constructed using standard AlInGaN or AlInGaP processing and comprises an LED chip II mounted in a reflective metal dish or reflector **12** filled with a transparent epoxy **13**.

FIG. **1**B schematically depicts a typical phosphor-LED **14** used in the invention. This LED **14** is substantially identical in construction to the LED of FIG. **1**A, except that the epoxy **18** filling the reflector **16** contains grains **19** of one or more types of luminescent phosphor materials mixed homogeneously therein. The phosphor grains **19** convert a portion of the light emitted by the LED chip **15** to light of a different spectral wavelength.

A primary advantage of the hybrid system of the invention is that it permits different lighting system performance parameters to be addressed and optimized as deemed important by varying the color and number of the LEDs and/or the phosphor of the phosphor-LED. In particular, the system of the present invention can address and achieve higher available lumens-per-chip averages via balancing red and green and blue light components; smaller integral numbers of LEDs at balance; improved color rendering; and more efficient mixing via the phosphor-LED. This in turn advantageously permits the manufacture of various types of products which are optimized for various applications using LED chips manufactured with standard AlInGaN and AlInGaP processing.

Each of the following embodiments illustrate how one or more of the above performance advantages can be achieved using the hybrid system of the invention. FIG. **2** schematically depicts a first embodiment of the hybrid lighting system of the invention denoted by numeral **20**. The system **20** comprises a red LED **22** that emits light having a spectral wavelength of about 610 nm and a phosphor-LED **24** consisting of a blue LED that emits light having a spectral wavelength of between about 450 nm and 470 nm, and a phosphor material that converts a portion (typically about 50%) of the blue light to green light having a spectral wavelength of about 550 nm. This embodiment of the inventive system provides reasonable power balance and achieves an overall system efficiency comparable with or exceeding conventional LED based lighting systems because it eliminates the need for a less efficient green LED (typically emits light having a spectral wavelength of about 530 nm) as employed in conventional LED based lighting systems (the phosphor LED could be fundamentally more efficient than the green LED chip because it has better access to the 550 nm range and thus, has a lumen-per-watt advantage). Moreover, the two LEDs **22, 24** of this embodiment of the system **20** are easier and more efficient to mix, and require less complex LED drive electronics than conventional lighting systems which typically employ three or four LEDs. More specifically, there are many mixing schemes for mixing LEDs. In virtually all of these schemes, less mixing is desirable. For example, in binary mixing schemes, only one mixing stage is required to mix the two LEDs **22, 24** of the inventive system **20** compared with two mixing stages required for conventional LED based lighting systems. Hence, approximately half the mixing losses of conventional LED based lighting systems are incurred with this embodiment of the system. Therefore, significantly higher overall system efficiency can be realized in this embodiment of the system when compared with conventional LED based lighting systems. Color rendering is adequate owing to the 550 nm light provided by the phosphor-LED **24** although the color point can only be adjusted along a line. Consequently, control over color temperature is only possible at the design point. However, such an embodiment of the invention is especially useful for producing a fixed white light in lower cost lighting system applications where less expensive LED drive electronics are desirable and truly versatile control over color temperature is not significantly important.

FIG. **3** schematically depicts a second embodiment of the hybrid lighting system of the invention denoted by numeral **30**. The system **30** comprises a red LED **32** (emits light having a spectral wavelength of about 610 nm), a green LED **34** (emits light having a spectral wavelength of about 530 nm) and a phosphor-LED **36** consisting of a blue LED (emits between ~450 nm and ~470 nm) and a phosphor material that converts a portion (about 50%) of the emitted blue light to red light (about 610 nm). In comparison to conventional LED based systems which typically produce insufficient quantities of red light and excessive quantities of blue light, the phosphor LED **36** used in this. embodiment of the inventive system balances the deficiency in red light output and attenuates the blue light output thereby providing good color balance with only three LEDs. Color rendering and color-temperature control is comparable to conventional LED based lighting systems. In particular, the use of three LEDs can provide maximum lumen content while permitting the color temperature to be freely adjusted, since the red content of the phosphor-LED **36** is sufficiently small to allow a balance to be struck by merely raising and lowering the brightness of the three LEDs via adjustments in the drive currents.

FIG. **4** schematically depicts a third embodiment of the hybrid lighting system of the invention denoted by numeral **40**. The system **40** comprises two red LEDs **42, 44** (emits at ~610 nm), a green LED **46** (emits at ~530 nm), and a phosphor-LED **48** consisting of a blue LED (emits between ~450 nm and ~470 nm) and a phosphor material that converts a portion of the blue light to green light having a spectral wavelength of about 550 nm. Since the phosphor has a power conversion efficiency of about 50%, sufficient quantities of blue and green light are generated by the phosphor-LED **48** thereby providing excellent balance and color rendering at the design point owing to the presence of the 550 nm light. Additionally, the 550 nm light produces much greater lumen content, thereby providing this embodiment of the system with a higher lumen output, even when the phosphor's conversion energy loss if factored in.

FIG. **5** schematically depicts a fourth embodiment of the hybrid lighting system of the invention denoted by numeral **50**. The system **50** is substantially identical to the system of the third embodiment in that it comprises two red LEDs **52, 54**, a green LED **56** and a phosphor-LED **58** that emits blue light and green light. However, the two red LEDs **52, 54** emit light at two slightly different spectral wavelengths (~610 nm and ~595 nm). The red LED emitting at about 595 nm produces a red color that is orange-amberlike to provide further improvements in color rendering.

FIG. **6** schematically depicts a fifth embodiment of the hybrid lighting system of the invention denoted by numeral **60**. The system **60** is substantially identical to the system of the third embodiment in that it comprises two red LEDs **62, 64**, a green LED **66** and a phosphor-LED **68**. However, the phosphor-LED **68** consists of a blue LED with a first phosphor material that emits at a light spectral wavelength of about 550 nm to convert a portion of the blue light to green light and a second phosphor material that converts a portion of the remaining blue light not converted by the first phosphor to an amber or yellow-green light. This embodiment exhibits further improvements in color rendering and is therefore useful in applications requiring maximized color rendering.

FIG. **7** schematically depicts a sixth embodiment of the hybrid lighting system of the invention denoted by numeral **70**. The system **70** combines the features of the fourth and fifth embodiments and thus, comprises a first red LED **72** (emits at ~610 nm), a second red LED **74** (emits at ~595 nm), a green LED (emits at ~530 nm) **76**, and a phosphor-LED **78**. The phosphor LED consists of a blue LED (emits between ~450 nm and ~470 nm) and a first phosphor material that emits at a light spectral wavelength of about 550 nm to convert a portion of the blue light to green light and a second phosphor material that converts a portion of the remaining blue light not converted by the first phosphor, to an amber or yellow-green light. This embodiment is also especially useful in applications requiring optimized color rendering.

While the foregoing invention has been described with reference to the above embodiments, various modifications and changes can be made without departing from the spirit of the invention. Accordingly, all such modifications and changes are considered to be within the scope of the appended claims.

What is claimed is:

1. A lighting system for producing white light, the system comprising:

at least one light emitting diode; and

a phosphor-light emitting diode disposed adjacent to the at least one light emitting diode.

2. The lighting system according to claim **1**, wherein the phosphor-light emitting diode emits at least two different colors of light.

3. The lighting system according to claim **1**, further comprising at least a second light emitting diode.

4. The lighting system according to claim **3** wherein the phosphor-light emitting diode emits at least two different colors of light, one of the at least two colors being at least substantially identical to the color emitted by at least one of the light emitting diodes.

5. The lighting system according to claim **3**, wherein the light emitted from the light emitting diodes are of the same general color but have different spectral wavelengths.

6. The lighting system according to claim **1**, further comprising second and third light emitting diodes.

7. The lighting system according to claim **6**, wherein the light emitted from two of the three light emitting diodes are of the same general color but have different spectral wavelengths.

8. The lighting system according to claim **7**, wherein the phosphor-light emitting diode emits at least three different colors of light.

9. The lighting system according to claim **6**, wherein the phosphor-light emitting diode emits at least three different colors of light.

10. The lighting system according to claim **6**, wherein the phosphor-light emitting diode emits at least two different colors of light.

11. The lighting system according to claim **1**, wherein the at least one light emitting diode emits red light.

12. The lighting system according to claim **11**, wherein the phosphor-light emitting diode includes a blue light emitting diode that emits blue light and at least one phosphor that converts at least a portion of the blue light to one of a green light and a red light.

13. The lighting system according to claim **12**, further comprising at least a second light emitting diode which emits green light.

14. The lighting system according to claim **13**, further comprising a third light emitting diode which emits red light.

15. The lighting system according to claim **14**, wherein the spectral wavelength of the red light emitted from the first light emitting diode is different from the spectral wavelength of the red light emitted from the third light emitting diode.

16. The lighting system according to claim **11**, further comprising at least a second light emitting diode which emits green light.

* * * * *

US006788011B2

(12) **United States Patent**
Mueller et al.

(10) **Patent No.: US 6,788,011 B2**
(45) **Date of Patent: Sep. 7, 2004**

(54) **MULTICOLORED LED LIGHTING METHOD AND APPARATUS**

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(73) Assignee: **Color Kinetics, Incorporated**, Boston, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/971,367**

(22) Filed: **Oct. 4, 2001**

(65) **Prior Publication Data**

US 2002/0057061 A1 May 16, 2002

Related U.S. Application Data

(63) Continuation of application No. 09/669,121, filed on Sep. 25, 2000, which is a continuation of application No. 09/425,770, filed on Oct. 22, 1999, now Pat. No. 6,150,774, which is a continuation of application No. 08/920,156, filed on Aug. 26, 1997, now Pat. No. 6,016,038.

(51) **Int. Cl.**[7] **G05F 1/00**

(52) **U.S. Cl.** **315/294**; 315/292; 315/312; 315/316; 315/362

(58) **Field of Search** 315/291, 292, 315/295, 294, 308, 312, 318, 314, 76, 360, 362, 316, 324; 362/800

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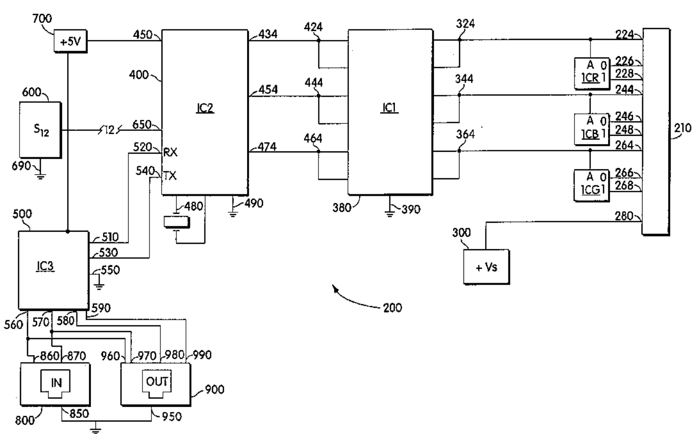
(57) **ABSTRACT**

The systems and methods described herein relate to LED systems capable of generating light, such as for illumination or display purposes. The light-emitting LEDs may be controlled by a processor to alter the brightness and/or color of the generated light, e.g., by using pulse-width modulated signals. Thus, the resulting illumination may be controlled by a computer program to provide complex, predesigned patterns of light in virtually any environment.

144 Claims, 7 Drawing Sheets



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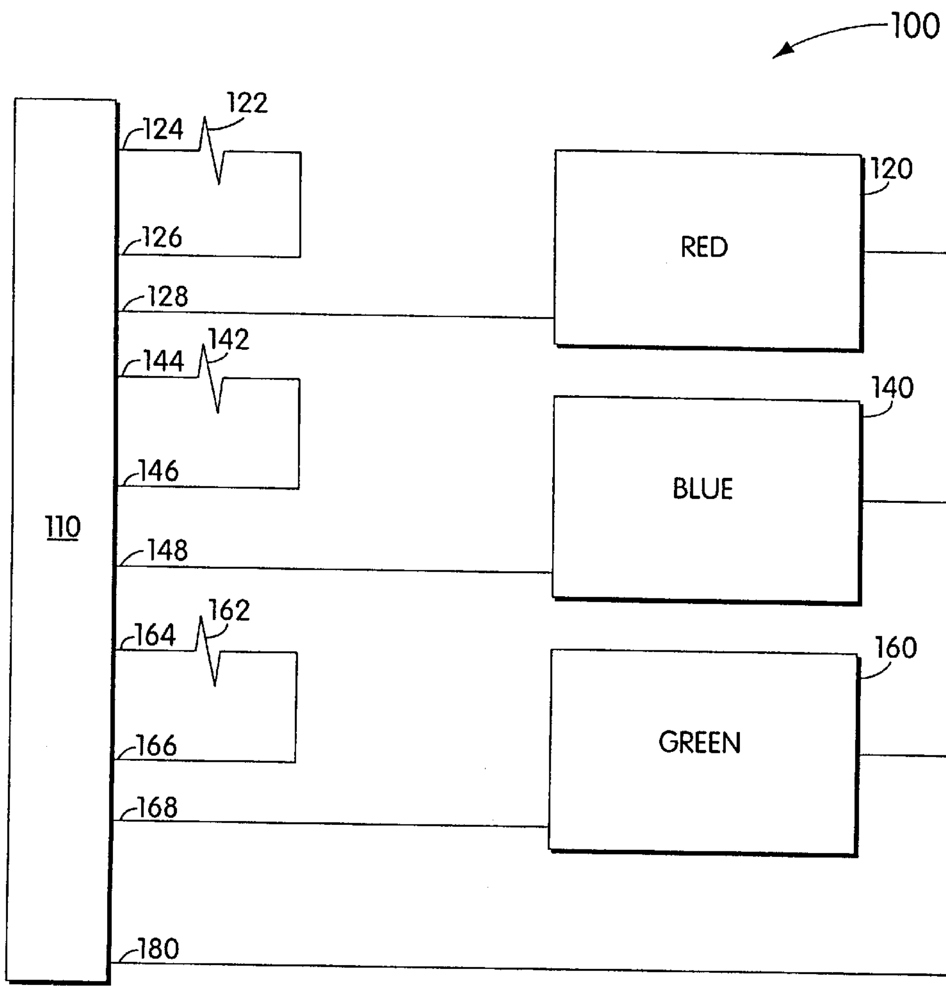
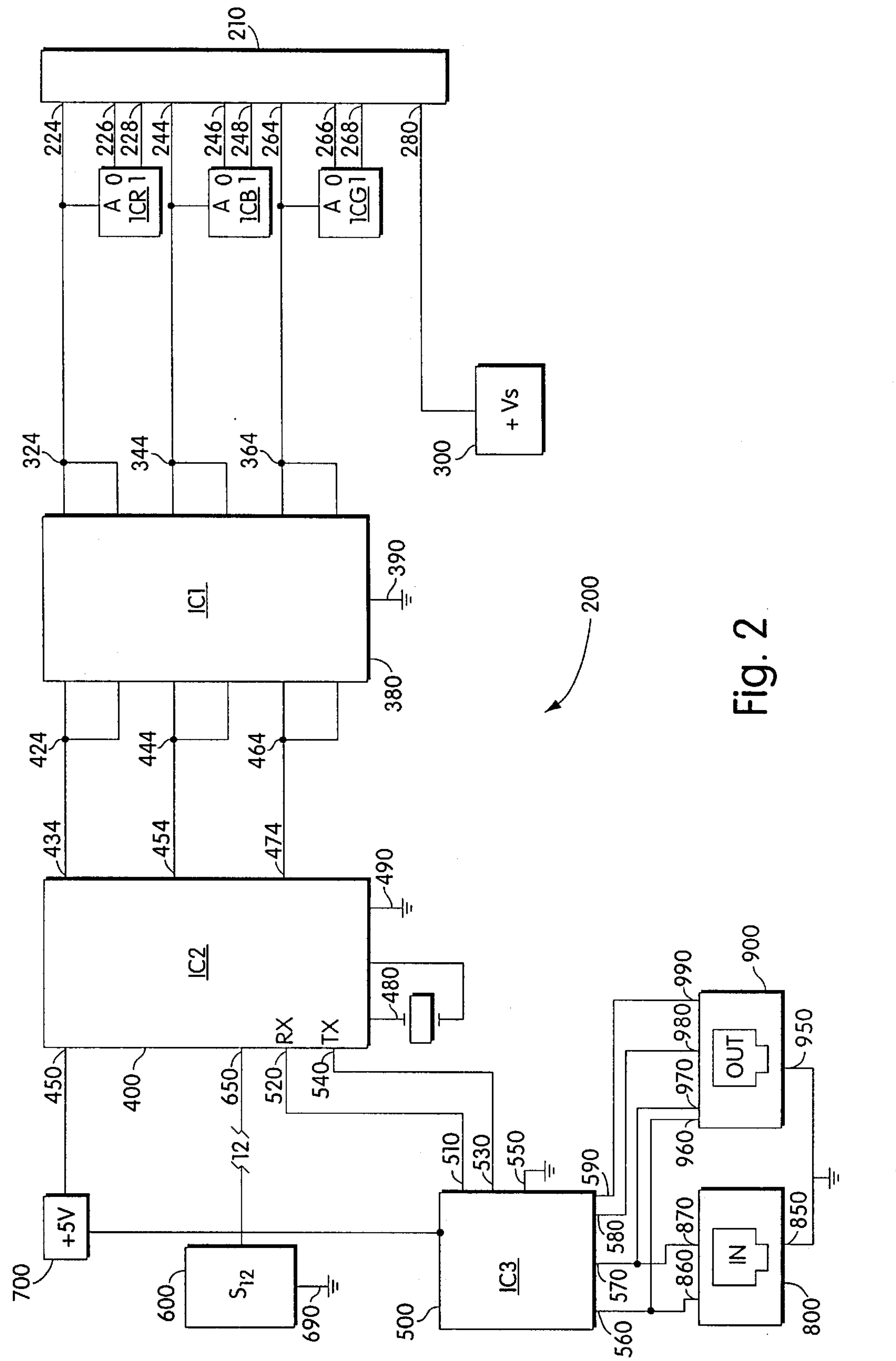

100
122
124
126
128
120
RED
142
144
146
140
BLUE
110
148
162
164
160
GREEN
166
168
180

Fig. 1



210
224
226
228
244
246
248
264
266
268
280
A 0
ICR1
A 0
ICB1
A 0
ICG1
+ Vs
300
324
344
364
IC1
390
380
200
424
444
464
434
454
474
IC2
490
480
RX
TX
450
400
650
520
540
12
+5V
700
S12
600
690
510
530
550
IC3
500
560
570
580
590
860
870
IN
850
800
OUT
950
900
990
980
970
960

Fig. 2

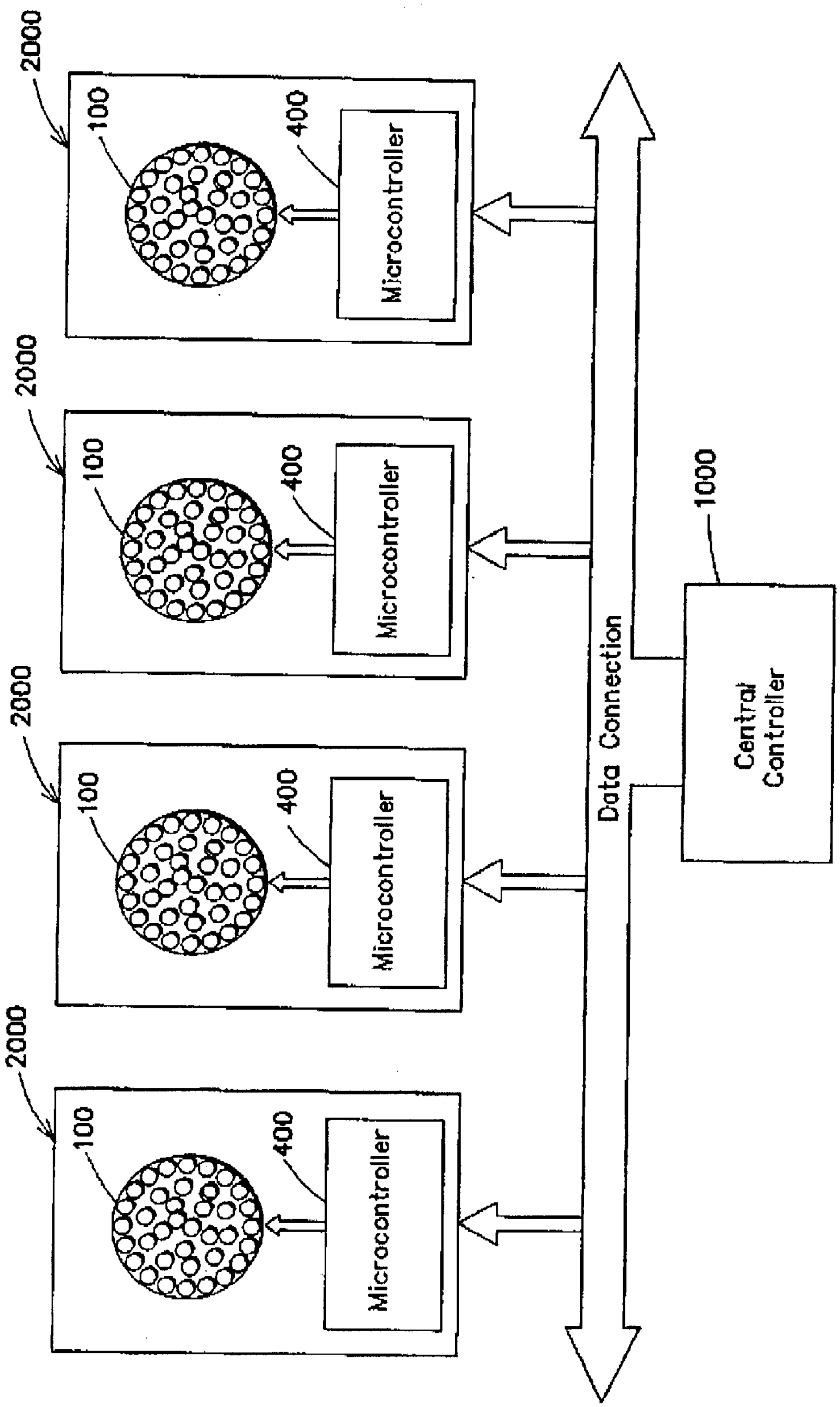

2000
100
400
Microcontroller
Data Connection
1000
Central Controller

Fig. 2A

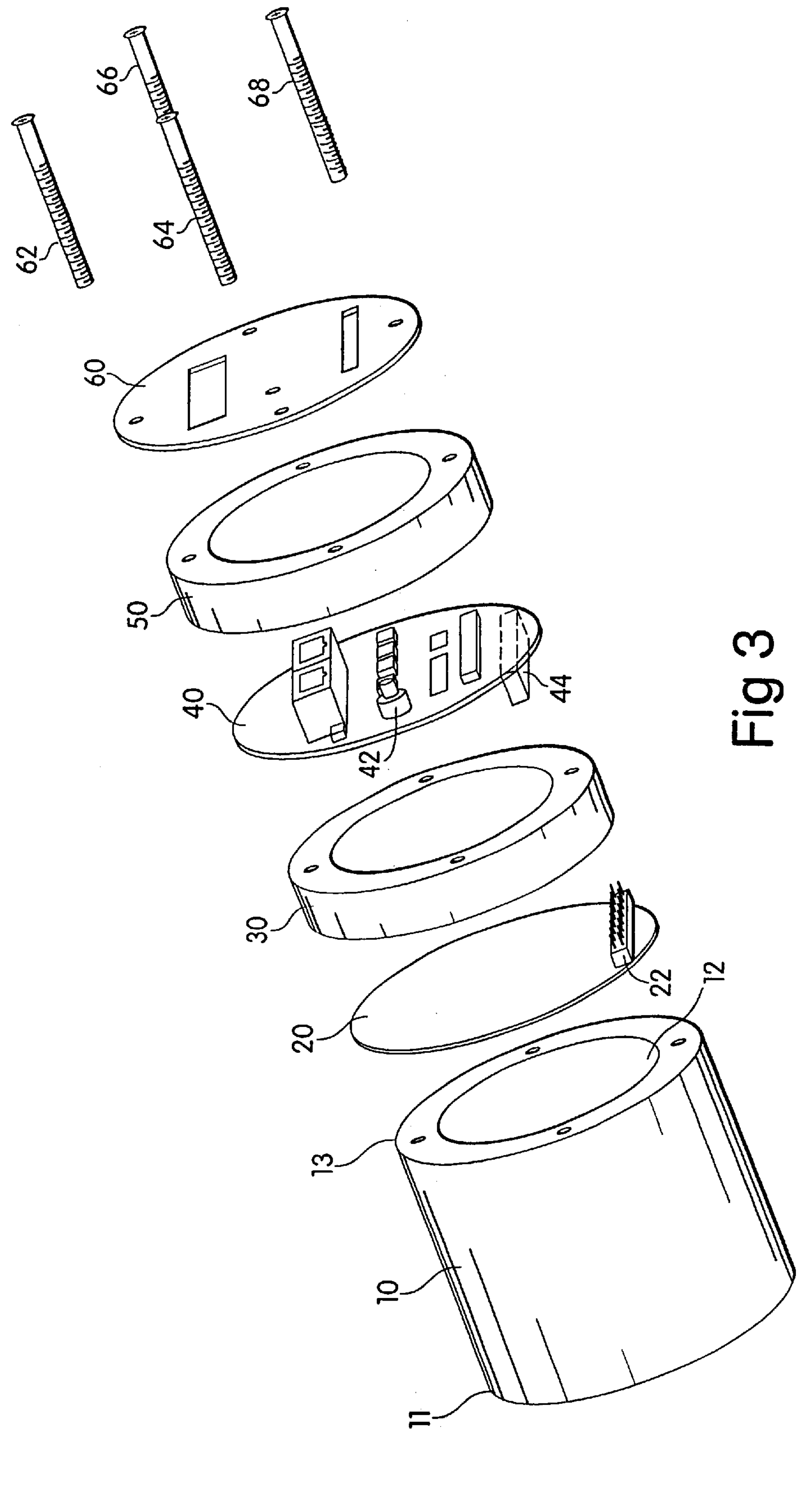


Fig 3

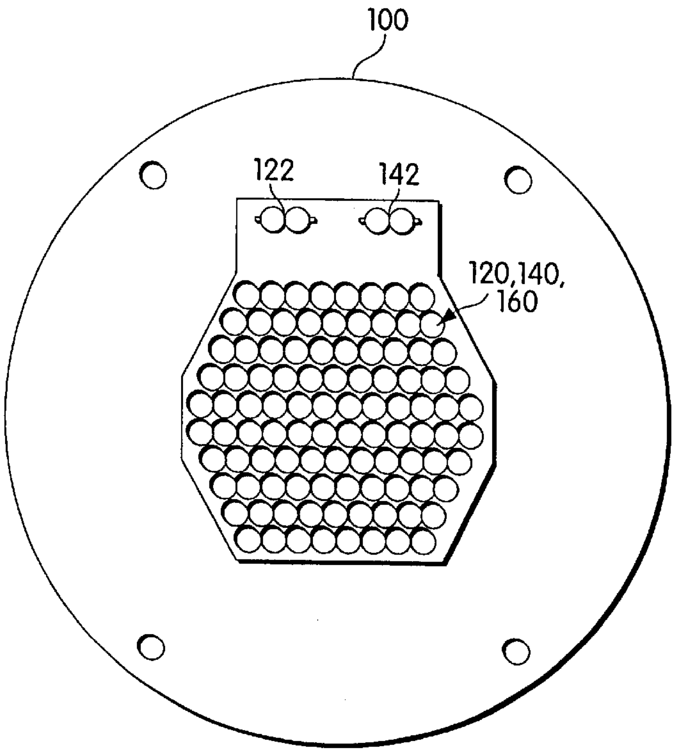


Fig. 4

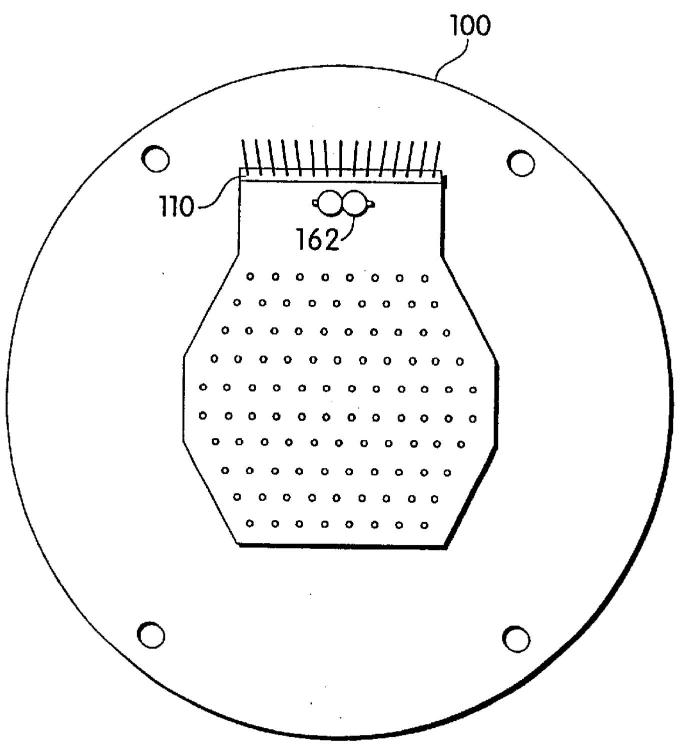


Fig. 5

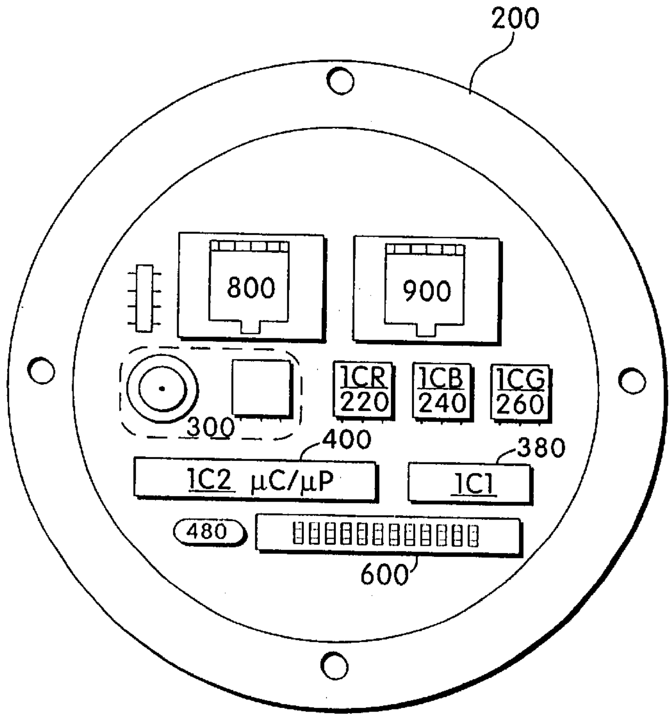

200
800
900
1CR
220
1CB
240
1CG
260
300
400
380
1C2 μC/μP
1C1
480
600

Fig. 6

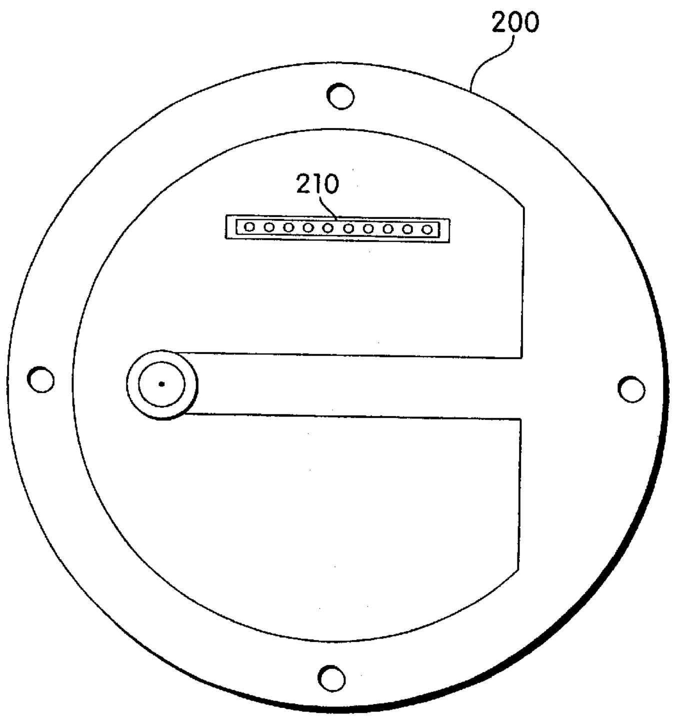

200
210

Fig. 7

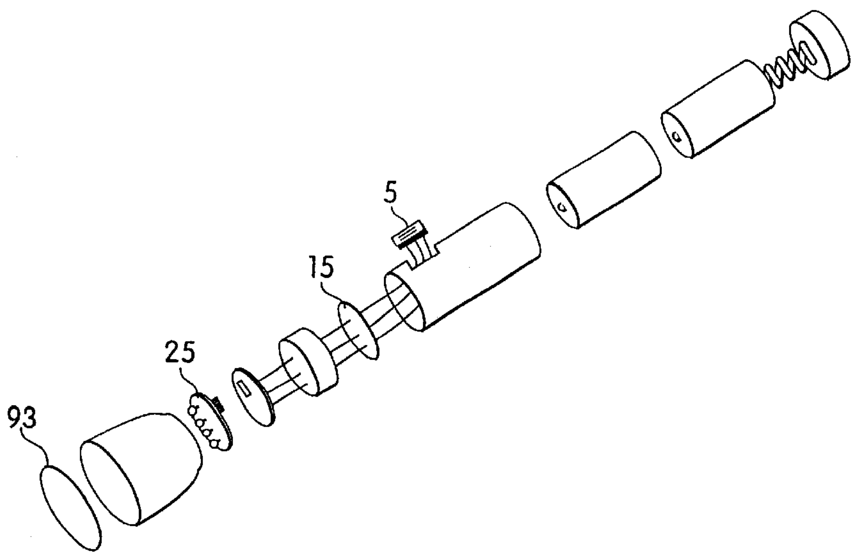

5
15
25
93

Fig. 8

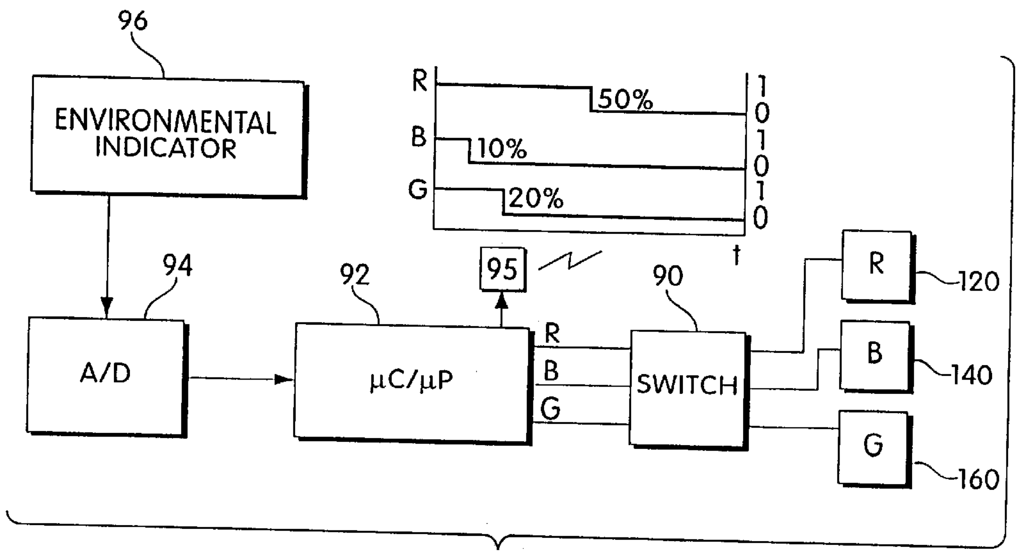

96
ENVIRONMENTAL INDICATOR
94
A/D
92
μC/μP
95
R
B
G
50%
10%
20%
1
0
1
0
1
0
t
90
SWITCH
R
B
G
120
140
160

Fig. 9

MULTICOLORED LED LIGHTING METHOD AND APPARATUS

CROSS REFERENCES TO RELATED APPLICATIONS

This application is a continuation of application Ser. No. 09/669,121, filed on Sep. 25, 2000, which is a continuation of application Ser. No. 09/425,770, filed Oct. 22, 1999, now U.S. Pat. No. 6,150,774, which is a continuation of application Ser. No. 08/920,156, filed Aug. 26, 1997, now U.S. Pat. No. 6,016,038.

BACKGROUND OF THE INVENTION

The present invention relates to providing light of a selectable color using LEDs. More particularly, the present invention is a method and apparatus for providing multicolored illumination. More particularly still, the present invention is an apparatus for providing a computer controlled multicolored illumination network capable of high performance and rapid color selection and change.

It is well known that combining the projected light of one color with the projected light of another color will result in the creation of a third color. It is also well known that the three most commonly used primary colors—red, blue and green—can be combined in different proportions to generate almost any color in the visible spectrum. The present invention takes advantage of these effects by combining the projected light from at least two light emitting diodes (LEDs) of different primary colors.

Computer lighting networks are not new. U.S. Pat. No. 5,420,482, issued to Phares, describes one such network that uses different colored LEDs to generate a selectable color. Phares is primarily for use as a display apparatus. However, the apparatus has several disadvantages and limitations. First, each of the three color LEDs in Phares is powered through a transistor biasing scheme in which the transistor base is coupled to a respective latch register through biasing resistors. The three latches are all simultaneously connected to the same data lines on the data bus. This means it is impossible in Phares to change all three LED transistor biases independently and simultaneously. Also, biasing of the transistors is inefficient because power delivered to the LEDs is smaller than that dissipated in the biasing network. This makes the device poorly suited for efficient illumination applications. The transistor biasing used by Phares also makes it difficult, if not impossible, to interchange groups of LEDs having different power ratings, and hence different intensity levels.

U.S. Pat. No. 4,845,481, issued to Havel, is directed to a multicolored display device. Havel addresses some, but not all of the switching problems associated with Phares. Havel uses a pulse width modulated signal to provide current to respective LEDs at a particular duty cycle. However, no provision is made for precise and rapid control over the colors emitted. As a stand alone unit, the apparatus in Havel suggests away from network lighting, and therefore lacks any teaching as to how to implement a pulse width modulated computer lighting network. Further, Havel does not appreciate the use of LEDs beyond mere displays, such as for illumination.

U.S. Pat. No. 5,184,114, issued to Brown, shows an LED display system. But Brown lacks any suggestion to use LEDs for illumination, or to use LEEDs in a configurable computer network environment. U.S. Pat. No. 5,134,387, issued to Smith et al., directed to an LED matrix display, contains similar problems. Its rudimentary cur-rent control scheme severely limits the possible range of colors that can be displayed.

It is an object of the present invention to overcome the limitations of the prior art by providing a high performance computer controlled multicolored LIED lighting network.

It is a further object of the present invention to provide a unique LED lighting network structure capable of both a linear chain of nodes and a binary tree configuration.

It is still another object of the present invention to provide a unique heat-dissipating housing to contain the lighting units of the lighting network.

It is yet another object of the present invention to provide a current regulated LED lighting apparatus, wherein the apparatus contains lighting modules each having its own maximum current rating and each conveniently interchangeable with one another.

It is a still further object of the present invention to provide a unique computer current-controlled LED lighting assembly for use as a general illumination device capable of emitting multiple colors in a continuously programmable 24-bit spectrum.

It is yet a still further object of the present invention to provide a unique flashlight, inclinometer, thermometer, general environmental indicator and lightbulb, all utilizing the general computer current-control principles of the present invention.

Other objects of the present invention will be apparent from the detailed description below.

SUMMARY OF THE INVENTION

In brief, the invention herein comprises a pulse width modulated current control for an LED lighting assembly, where each current-controlled unit is uniquely addressable and capable of receiving illumination color information on a computer lighting network. In a further embodiment, the invention includes a binary tree network configuration of lighting units (nodes). In another embodiment, the present invention comprises a heat dissipating housing, made out of a heat-conductive material, for housing the lighting assembly. The heat dissipating housing contains two stacked circuit boards holding respectively the power module and the light module. The light module is adapted to be conveniently interchanged with other light modules having programmable current, and hence maximum light intensity ratings. Other embodiments of the present invention involve novel applications for the general principles described herein.

DESCRIPTION OF THE DRAWINGS

FIG. **1** is a stylized electrical circuit schematic of the light module of the present invention.

FIG. **2** is a stylized electrical circuit schematic of the power module of the present invention.

FIG. **2**A illustrates a network of addressable LED-based lighting units according to one embodiment of the invention.

FIG. **3** is an exploded view of the housing of one of the embodiments of the present invention.

FIG. **4** is a plan view of the LED-containing side of the light module of the present invention.

FIG. **5** is a plan view of the electrical connector side of the light module of the present invention.

FIG. **6** is a plan view of the power terminal side of the power module of the present invention.

FIG. **7** is a plan view of the electrical connector side of the power module of the present invention.

FIG. **8** is an exploded view of a flashlight assembly containing the LED lighting module of the present invention.

FIG. 9 is a control block diagram of the environmental indicator of the present invention.

DETAILED DESCRIPTION

The structure and operation of a preferred embodiment will now be described. It should be understood that many other ways of practicing the inventions herein are available, and the embodiments described herein are exemplary and not limiting. Turning to FIG. **1**, shown is an electrical schematic representation of a light module **100** of the present invention. FIGS. **4** and **5** show the LED-containing side and the electrical connector side of light module **100**. Light module **100** is self-contained, and is configured to be a standard item interchangeable with any similarly constructed light module. Light module **100** contains a ten-pin electrical connector **110** of the general type. In this embodiment, the connector **110** contains male pins adapted to fit into a complementary ten-pin connector female assembly, to be described below. Pin **180** is the power supply. A source of DC electrical potential enters module **100** on pin **180**. Pin **180** is electrically connected to the anode end of light emitting diode (LED) sets **120**, **140** and **160** to establish a uniform high potential on each anode end.

LED set **120** contains red LEDs, set **140** contains blue and set **160** contains green, each obtainable from the Nichia America Corporation. These LEDs are primary colors, in the sense that such colors when combined in preselected proportions can generate any color in the spectrum. While three primary colors is preferred, it will be understood that the present invention will function nearly as well with only two primary colors to generate any color in the spectrum. Likewise, while the different primary colors are arranged herein on sets of uniformly colored LEDs, it will be appreciated that the same effect may be achieved with single LEDs containing multiple color-emitting semiconductor dies. LED sets **120**, **140** and **160** each preferably contains a serial/parallel array of LEDs in the manner described by Okuno in U.S. Pat. No. 4,298,869, incorporated herein by reference. In the present embodiment, LED set **120** contains three parallel connected rows of nine red LEDs (not shown), and LED sets **140** and **160** each contain five parallel connected rows of five blue and green LEDs, respectively (not shown). It is understood by those in the art that, in general, each red LED drops the potential in the line by a lower amount than each blue or green LED, about 2.1 V, compared to 4.0 V, respectively, which accounts for the different row lengths. This is because the number of LEDs in each row is determined by the amount of voltage drop desired between the anode end at the power supply voltage and the cathode end of the last LED in the row. Also, the parallel arrangement of rows is a fail-safe measure that ensures that the light module **100** will still function even if a single LED in a row fails, thus opening the electrical circuit in that row. The cathode ends of the three parallel rows of nine red LEDs in LED set **120** are then connected in common, and go to pin **128** on connector **110**. Likewise, the cathode ends of the five parallel rows of five blue LEDs in LED set **140** are connected in common, and go to pin **148** on connector **110**. The cathode ends of the five parallel rows of five green LEDs in LED set **160** are connected in common, and go to pin **168** on connector **110**. Finally, on light module **100**, each LED set is associated with a programming resistor that combines with other components, described below, to program the maximum current through each set of LEDs. Between pin **124** and **126** is resistor **122**, 6.2 Ω. Between pin **144** and **146** is resistor **142**, 4.7 Ω. Between pin **164** and **166** is resistor **162**, 4.7 Ω. Resistor **122** programs maximum current through red LED set **120**, resistor **142** programs maximum current through blue LED set **140**, and resistor **162** programs maximum current through green LED set **160**. The values these resistors should take are determined empirically, based on the desired maximum light intensity of each LED set. In the present embodiment, the resistances above program red, blue and green currents of 70, 50 and 50 μA, respectively.

With the electrical structure of light module **100** described, attention will now be given to the electrical structure of power module **200**, shown in FIG. **2**. FIGS. **6** and **7** show the power terminal side and electrical connector side of an embodiment of power module **200**. Like light module **100**, power module **200** is self contained. Interconnection with male pin set **110** is achieved through complementary female pin set **210**. Pin **280** connects with pin **180** for supplying power, delivered to pin **280** from supply **300**. Supply **300** is shown as a functional block for simplicity. In actuality, supply **300** can take numerous forms for generating a DC voltage. In the present embodiment, supply **300** provides 24 Volts through a connection terminal (not shown), coupled to pin **280** through transient protection capacitors (not shown) of the general type. It will be appreciated that supply **300** may also supply a DC voltage after rectification and/or voltage transformation of an AC supply, as described more fully in U.S. Pat. No. 4,298,869.

Also connected to pin connector **210** are three current programming integrated circuits, ICR **220**, ICB **240** and ICG **260**. Each of these is a three terminal adjustable regulator, preferably part number LM317B, available from the National Semiconductor Corporation, Santa Clara, Calif. The teachings of the LM317 datasheet are incorporated herein by reference. Each regulator contains an input terminal, an output terminal and an adjustment terminal, labeled I, O and A, respectively. The regulators function to maintain a constant maximum current into the input terminal and out of the output terminal. This maximum current is pre-programmed by setting a resistance between the output and the adjustment terminals. This is because the regulator will cause the voltage at the input terminal to settle to whatever value is needed to cause 1.25 V to appear across the fixed current set resistor, thus causing constant current to flow. Since each functions identically, only ICR **220** will now be described. First, current enters the input terminal of ICR **220** from pin **228**. Of course, pin **228** in the power module is coupled to pin **128** in the light module, and receives current directly from the cathode end of the red LED set **120**. Since resistor **122** is ordinarily disposed between the output and adjustment terminals of ICR **220** through pins **224**/**124** and **226**/**126**, resistor **122** programs the amount of current regulated by ICR **220**. Eventually, the current output from the adjustment terminal of ICR **220** enters a Darlington driver. In this way, ICR **220** and associated resistor **122** program the maximum current through red LED set **120**. Similar results are achieved with ICB **240** and resistor **142** for blue LED set **140**, and with ICG **260** and resistor **162** for green LED set **160**.

The red, blue and green LED currents enter another integrated circuit, IC**1** **380**, at respective nodes **324**, **344** and **364**. IC**1** **380** is preferably a high current/voltage Darlington driver, part no. DS2003 available from the National Semiconductor Corporation, Santa Clara, Calif. IC**1** **380** is used as a current sink, and functions to switch current between respective LED sets and ground **390**. As described in the DS2003 datasheet, incorporated herein by reference, IC**1** contains six sets of Darlington transistors with appropriate on-board biasing resistors. As shown, nodes **324**, **344** and **364** couple the current from the respective LED sets to three

pairs of these Darlington transistors, in the well known manner to take advantage of the fact that the current rating of IC1 **380** may be doubled by using pairs of Darlington transistors to sink respective currents. Each of the three on-board Darlington pairs is used in the following manner as a switch. The base of each Darlington pair is coupled to signal inputs **424**, **444** and **464**, respectively. Hence, input **424** is the signal input for switching current through node **324**, and thus the red LED set **120**. Input **444** is the signal input for switching current through node **344**, and thus the blue LED set **140**. Input **464** is the signal input for switching current through node **364**, and thus the green LED set **160**. Signal inputs **424**, **444** and **464** are coupled to respective signal outputs **434**, **454** and **474** on microcontroller IC2 **400**, as described below. In essence, when a high frequency square wave is incident on a respective signal input, IC1 **380** switches current through a respective node with the identical frequency and duty cycle. Thus, in operation, the states of signal inputs **424**, **444** and **464** directly correlate with the opening and closing of the power circuit through respective LED sets **120**, **140** and **160**.

The structure and operation of microcontroller IC2 **400** will now be described. Microcontroller IC2 **400** is preferably a MICROCHIP brand PIC 16C63, although almost any properly programmed microcontroller or microprocessor can perform the software functions described herein. The main function of microcontroller IC2 **400** is to convert numerical data received on serial Rx pin **520** into three independent high frequency square waves of uniform frequency but independent duty cycles on signal output pins **434**, **454** and **474**. The FIG. **2** representation of microcontroller IC2 **400** is partially stylized, in that persons of skill in the art will appreciate that certain of the twenty-eight standard pins have been omitted or combined for greatest clarity.

Microcontroller IC2 **400** is powered through pin **450**, which is coupled to a 5 Volt source of DC power **700**. Source **700** is preferably driven from supply **300** through a coupling (not shown) that includes a voltage regulator (not shown). An exemplary voltage regulator is the LM340 3-terminal positive regulator, available from the National Semiconductor Corporation, Santa Clara, Calif. The teachings of the LM340 datasheet are hereby incorporated by reference. Those of skill in the art will appreciate that most microcontrollers, and many other independently powered digital integrated circuits, are rated for no more than a 5 Volt power source. The clock frequency of microcontroller IC2 **400** is set by crystal **480**, coupled through appropriate pins. Pin **490** is the microcontroller IC2 **400** ground reference.

Switch **600** is a twelve position dip switch that may be alterably and mechanically set to uniquely identify the microcontroller IC2 **400**. When individual ones of the twelve mechanical switches within dip switch **600** are closed, a path is generated from corresponding pins **650** on microcontroller IC2 **400** to ground **690**. Twelve switches create 2^{12} possible settings, allowing any microcontroller IC2 **400** to take on one of 4096 different IDs, or addresses. In the preferred embodiment, only nine switches are actually used because the DMX-512 protocol, discussed below, is employed.

Once switch **600** is set, microcontroller IC2 **400** "knows" its unique address ("who am I"), and "listens" on serial line **520** for a data stream specifically addressed to it. A high speed network protocol, preferably a DMX protocol, is used to address network data to each individually addressed microcontroller IC2 **400** from a central network controller **1000**, as shown for example in FIG. **2A**. The DMX protocol is described in a United States Theatre Technology, Inc. publication entitled "DMX512/1990 Digital Data Transmission Standard for Dimmers and Controllers," incorporated herein by reference. Basically, in the network protocol used herein, a central controller creates a stream of network data consisting of sequential data packets. Each packet first contains a header, which is checked for conformance to the standard and discarded, followed by a stream of sequential bytes representing data for sequentially addressed devices. For instance, if the data packet is intended for light number fifteen, then fourteen bytes from the data stream will be discarded, and the device will save byte number fifteen. If as in the preferred embodiment, more than one byte is needed, then the address is considered to be a starting address, and more than one byte is saved and utilized. Each byte corresponds to a decimal number 0 to 255, linearly representing the desired intensity from Off to Full. (For simplicity, details of the data packets such as headers and stop bits are omitted from this description, and will be well appreciated by those of skill in the art.) This way, each of the three LED colors is assigned a discrete intensity value between 0 and 255. These respective intensity values are stored in respective registers within the memory of microcontroller IC2 **400** (not shown). Once tile central controller exhausts all data packets, it starts over in a continuous refresh cycle. The refresh cycle is defined by the standard to be a minimum of 1196 microseconds, and a maximum of 1 second.

Microcontroller IC2 **400** is programmed continually to "listen" for its data stream. When microcontroller IC2 **400** is "listening," but before it detects a data packet intended for it, it is running a routine designed to create the square wave signal outputs on pins **434**, **454** and **474**. The values in the color registers determine the duty cycle of the square wave. Since each register can take on a value from 0 to 255, these values create 256 possible different duty cycles in a linear range from 0% to 100%. Since the square wave frequency is uniform and determined by the program running in the microcontroller IC2 **400**, these different discrete duty cycles represent variations in the width of the square wave pulses. This is known as pulse width modulation (PWM).

The PWM interrupt routine is implemented using a simple counter, incrementing from 0 to 255 in a cycle during each period of the square wave output on pins **434**, **454** and **474**. When the counter rolls over to zero, all three signals are set high. Once the counter equals the register value, signal output is changed to low. When microcontroller IC2 **400** receives new data, it freezes the counter, copies the new data to the working registers, compares the new register values with the current count and updates the output pins accordingly, and then restarts the counter exactly where it left off. Thus, intensity values may be updated in the middle of the PWM cycle. Freezing the counter and simultaneously updating the signal outputs has at least two advantages. First, it allows each lighting unit to quickly pulse/strobe as a strobe light does. Such strobing happens when the central controller sends network data having high intensity values alternately with network data having zero intensity values at a rapid rate. If one restarted the counter without first updating the signal outputs, then the human eye would be able to perceive the staggered deactivation of each individual color LED that is set at a different pulse width. This feature is not of concern in incandescent lights because of the integrating effect associated with the heating and cooling cycle of the illumination element. LEDs, unlike incandescent elements, activate and deactivate essentially instantaneously in the present application. The second advantage is that one can "dim" the LEDs without the flickering that

would otherwise occur if the counter were reset to zero. The central controller can send a continuous dimming signal when it creates a sequence of intensity values representing a uniform and proportional decrease in light intensity for each color LED. If one did not update the output signals before restarting the counter, there is a possibility that a single color LED will go through nearly two cycles without experiencing the zero current state of its duty cycle. For instance, assume the red register is set at 4 and the counter is set at 3 when it is frozen. Here, the counter is frozen just before the "off" part of the PWM cycle is to occur for the red LEDs. Now assume that the network data changes the value in the red register from 4 to 2 and the counter is restarted without deactivating the output signal. Even though the counter is greater than the intensity value in the red register, the output state is still "on", meaning that maximum current is still flowing through the red LEDs. Meanwhile, the blue and green LEDs will probably turn off at their appropriate times in the PWM cycle. This would be perceived by the human eye as a red flicker in the course of dimming the color intensities. Freezing the counter and updating the output for the rest of the PWM cycle overcomes these disadvantages, ensuring the flicker does not occur.

The network interface for microcontroller IC**2** **400** will now be described. Jacks **800** and **900** are standard RJ-8 network jacks. Jack **800** is used as an input jack, and is shown for simplicity as having only three inputs: signal inputs **860**, **870** and ground **850**. Network data enters jack **800** and passes through signal inputs **860** and **870**. These signal inputs are then coupled to IC**3** **500**, which is an RS-485/RS-422 differential bus repeater of the standard type, preferably a DS96177 from the National Semiconductor Corporation, Santa Clara, Calif. The teachings of the DS96177 datasheet are hereby incorporated by reference. The signal inputs **860**, **870** enter IC**3** **500** at pins **560**, **570**. The data signal is passed through from pin **510** to pin **520** on microcontroller IC**2** **400**. The same data signal is then returned from pin **540** on IC**2** **400** to pin **530** on IC**3** **500**. Jack **900** is used as an output jack and is shown for simplicity as having only five outputs: signal outputs **960**, **970**, **980**, **990** and ground **950**. Outputs **960** and **970** are split directly from input lines **860** and **870**, respectively. Outputs **980** and **990** come directly from IC**3** **500** pins **580** and **590**, respectively. It will be appreciated that the foregoing assembly enables two network nodes to be connected for receiving the network data. Thus, a network may be constructed as a daisy chain, if only single nodes are strung together, or as a binary tree, if two nodes are attached to the output of each single node.

From the foregoing description, one can see that an addressable network of LED illumination or display units **2000** as shown in FIG. **2**A can be constructed from a collection of power modules each connected to a respective light module. As long as at least two primary color LEDs are used, any illumination or display color may be generated simply by preselecting the light intensity that each color emits. Further, each color LED can emit light at any of 255 different intensities, depending on the dug cycle of PWM square wave, with a full intensity pulse generated by passing maximum current through the LED. Further still, the maximum intensity can be conveniently programmed simply by adjusting the ceiling for the maximum allowable current using programming resistances for the current regulators residing on the light module. Light modules of different maximum current ratings may thereby be conveniently interchanged.

The foregoing embodiment may reside in any number of different housings. A preferred housing for an illumination unit is described. Turning now to FIG. **3**, there is shown an exploded view of an illumination unit of the present invention comprising a substantially cylindrical body section **10**, a light module **20**, a conductive sleeve **30**, a power module **40**, a second conductive sleeve **50** and an enclosure plate **60**. It is to be assumed here that the light module **20** and the power module **40** contain the electrical structure and software of light module **100** and power module **200**, described above. Screws **62**, **64**, **66**, **68** allow the entire apparatus to be mechanically connected. Body section **10**, conductive sleeves **30** and **50** and enclosure plate **60** are preferably made from a material that conducts heat, most preferably aluminum. Body section **10** has an open end **10**, a reflective interior portion **12** and an illumination end **13**, to which module **20** is mechanically affixed. Light module **20** is disk shaped and has two sides. The illumination side (not shown) comprises a plurality of LEDs of different primary colors. The connection side holds an electrical connector male pin assembly **22**. Both the illumination side and the connection side are coated with aluminum surfaces to better allow the conduction of heat outward from the plurality of LEDs to the body section **10**. Likewise, power module **40** is disk shaped and has every available surface covered with aluminum for the same reason. Power module **40** has a connection side holding an electrical connector female pin assembly **44** adapted to fit the pins from assembly **22**. Power module **40** has a power terminal side holding a terminal **42** for connection to a source of DC power. Any standard AC or DC jack may be used, as appropriate.

Interposed between light module **20** and power module **40** is a conductive aluminum sleeve **30**, which substantially encloses the space between modules **20** and **40**. As shown, a disk-shaped enclosure plate **60** and screws **62**, **64**, **66** and **68** sad all of the components together, and conductive sleeve **50** is thus interposed between enclosure plate **60** and power module **40**. Once sealed together as a unit, the illumination apparatus may be connected to a data network as described above and mounted in any convenient manner to illuminate an area. In operation, preferably a light diffusing means will be inserted in body section **10** to ensure that the LEDs on light module **20** appear to emit a single uniform frequency of light.

From the foregoing, it will be appreciated that PWM current control of LEDs to produce multiple colors may be incorporated into countless environments, with or without networks. For instance, FIG. **8** shows a hand-held flashlight can be made to shine any conceivable color using an LED assembly of the present invention. The flashlight contains an external adjustment means **5**, that may be for instance a set of three potentiometers coupled to an appropriately programmed microcontroller **92** through respective A/D conversion means **15**. Each potentiometer would control the current duty cycle, and thus the illumination intensity, of an individual color LED on LED board **25**. With three settings each capable of generating a different byte from 0 to 255, a computer-controlled flashlight may generate twenty-four bit color. Of course, three individual potentiometers can be incorporated into a single device such as a track ball or joystick, so as to be operable as a single adjuster. Further, it is not necessary that the adjustment means must be a potentiometer. For instance, a capacitive or resistive thumb plate may also be used to program the two or three registers necessary to set the color. A lens assembly **93** may be provided for reflecting the emitted light. A non-hand held embodiment of the present invention may be used as an underwater swimming pool light. Since the present invention can operate at relatively low voltages and low current, it is uniquely suited for safe underwater operation.

Similarly, the present invention may be used as a general indicator of any given environmental condition. FIG. **9** shows the general functional block diagram for such an apparatus. Shown within FIG. **9** is also an exemplary chart showing the duty cycles of the three color LEDs during an exemplary period. As one example of an environmental indicator **96**, the power module can be coupled to an inclinometer. The inclinometer measures general angular orientation with respect to the earth's center of gravity. The inclinometer's angle signal can be converted through an A/D converter **94** and coupled to the data inputs of the microcontroller **92** in the power module. The microcontroller **92** can then be programmed to assign each discrete angular orientation a different color through the use of a lookup table associating angles with LED color register values. A current switch **90**, coupled to the microcontroller **92**, may be used to control the current supply to LEDs **120**, **140**, and **160** of different colors. The microcontroller **92** may be coupled to a transceiver **95** for transmitting and receiving signals. The "color inclinometer" may be used for safety, such as in airplane cockpits, or for novelty, such as to illuminate the sails on a sailboat that sways in the water. Another indicator use is to provide an easily readable visual temperature indication. For example, a digital thermometer can be connected to provide the microcontroller a temperature reading Each temperature will be associated with a particular set of register values, and hence a particular color output A plurality of such "color thermometers" can be located over a large space, such as a storage freezer, to allow simple visual inspection of temperature over three dimensions.

Another use of the present invention is as a lightbulb. Using appropriate rectifier and voltage transformation means, the entire power and light modules may be placed in an Edison-mount (screw-type) lightbulb housing. Each bulb can be programmed with particular register values to deliver a particular color bulb, including white. The current regulator can be pre-programmed to give a desired current rating and thus preset light intensity. Naturally, the lightbulb will have a transparent or translucent section that allows the passage of light into the ambient.

While the foregoing has been a detailed description of the preferred embodiment of the invention, the claims which follow define more freely the scope of invention to which applicant is entitled. Modifications or improvements which may not come within the explicit language of the claims described in the preferred embodiments should be treated as within the scope of invention insofar as they are equivalent or otherwise consistent with the contribution over the prior art and such contribution is not to be limited to specific embodiments disclosed.

What is claimed is:

1. An illumination apparatus, comprising:

at least one first LED adapted to output at least first radiation having a first spectrum;

at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum; and

at least one controller coupled to the at least one first LED and the at least one second LED and configured to respond to user operation of at least one user interface in communication with the at least one controller, the at least one controller further configured to independently control at least a first intensity of the first radiation and a second intensity of the second radiation in response to the user operation,

wherein the at least one controller is configured to implement a pulse width modulation (PWM) technique to control at least the first intensity of the first radiation and the second intensity of the second radiation.

2. The illumination apparatus of claim **1**, wherein the at least one controller is configured as an addressable controller capable of receiving at least one network signal including address information and lighting information.

3. The illumination apparatus of claim **1**, wherein the at least one controller is configured to independently control at least the first intensity of the first radiation and the second intensity of the second radiation so as to controllably vary an overall color generated by the apparatus as perceived by an observer.

4. The illumination apparatus of claim **1**, wherein the at least one controller is configured to independently control at least the first intensity of the first radiation and the second intensity of the second radiation such that an overall color generated by the illumination apparatus represents a single observable color at a given time.

5. The illumination apparatus of claim **1**, wherein the at least one controller is configured to independently control at least the first intensity of the first radiation and the second intensity of the second radiation so as to controllably vary an overall intensity of illumination generated by the apparatus as perceived by an observer.

6. The illumination apparatus of claim **1**, wherein the at least one controller is configured to independently control at least the first intensity of the first radiation and the second intensity of the second radiation so as to produce a dynamic lighting effect as perceived by an observer.

7. The illumination apparatus of claim **1**, further comprising at least one third LED adapted to output third radiation having a third spectrum different than the first spectrum and the second spectrum, wherein the at least one controller is further adapted to independently control a third intensity of the third radiation in response to the user operation of the at least one user interface.

8. The illumination apparatus of claim **7**, wherein at least one of the at least one first LED, the at least one second LED, and the at least one third LED includes at least one blue LED.

9. The illumination apparatus of claim **8**, wherein the at least one first LED, the at least one second LED, and the at least one third LED respectively include at least one red LED, at least one green LED, and at least one blue LED.

10. The illumination apparatus of claim **1**, further comprising at least one optical element disposed in a path of at least the first radiation and the second radiation to optically process at least the first radiation and the second radiation.

11. The illumination apparatus of claim **10**, wherein the at least one optical element is configured to receive at least the first and second radiation and to display a color that is a combination of at least the first and second radiation.

12. The illumination apparatus of claim **1**, further including at least one sensor to monitor at least one detectable condition, wherein the at least one controller is configured to further control the at least one first LED and the at least one second LED in response to the at least one detectable condition.

13. The illumination apparatus of claim **1**, further including at least one transceiver coupled to the at least one controller and configured to communicate at least one IR signal or at least one electromagnetic signal.

14. The illumination apparatus of claim **1**, wherein:

the at least one controller includes at least one first register associated with the at least one first LED and at least one second register associated with the at least one second LED; and

the at least one controller is configured to program the at least one first register and the at least one second register based on the user operation.

15. The illumination apparatus of claim **1**, wherein the at least one controller includes at least one adjustable regulator configured to variably regulate power to at least one of the at least one first LED and the at least one second LED.

16. The illumination apparatus of claim **1**, wherein:

the at least one controller includes a first switch and a second switch respectively associated with the at least one first LED and the at least one second LED; and

the at least one controller is configured to control the at least one first LED and the at least one second LED by turning the first and second switches on and off at high speeds.

17. The illumination apparatus of claim **2**, wherein:

the addressable controller includes a first switch and a second switch respectively associated with the at least one first LED and the at least one second LED; and

the addressable controller is configured to control the at least one first LED and the at least one second LED by turning the first and second switches on and off at high speeds.

18. The illumination apparatus of claim **1**, wherein the at least one controller is configured to implement the PWM technique such that at least one potentially observable artifact in at least the first radiation and the second radiation is reduced.

19. The illumination apparatus of claim **18**, wherein the at least one potentially observable artifact includes a flicker effect, and wherein the at least one controller is configured to implement the PWM technique such that the flicker effect is reduced.

20. The illumination apparatus of claim **19**, wherein the at least one controller is configured to be capable of varying an overall intensity of illumination generated by the apparatus with essentially no perceivable flicker effect.

21. The illumination apparatus of claim **18**, wherein the at least one controller includes:

at least one first register associated with the at least one first LED to store a first intensity value representing a first PWM control signal;

at least one second register associated with the at least one second LED to store a second intensity value representing a second PWM control signal; and

at least one PWM counter,

wherein:

the at least one controller is configured to program at least the at least one first register and the at least one second register with the first and second intensity values, respectively, based on the user operation; and

the at least one controller is configured to generate the first and second PWM control signals based on a comparison of the at least one PWM counter to the first and second intensity values, respectively.

22. The illumination apparatus of claim **21**, wherein the first and second intensity values represent respective duty cycles of the first and second PWM control signals.

23. The illumination apparatus of claim **21**, wherein the at least one controller is configured to freeze the at least one PWM counter when at least one of the at least one first register and the at least one second register is programmed with a new intensity value.

24. The illumination apparatus of claim **23**, wherein the at least one controller is configured to update at least one of the first PWM control signal and the second PWM control signal based on the new intensity value after the at least one PWM counter is frozen, and then restart the at least one PWM counter where it left off after the at least one of the first PWM control signal and the second PWM control signal is updated.

25. The illumination apparatus of claim **1**, wherein the at least one controller includes at least one modular connection to facilitate coupling of the at least one controller to the at least one first LED and the at least one second LED.

26. The illumination apparatus of claim **25**, wherein:

the at least one first LED and the at least one second LED are supported by a first substrate;

the at least one controller is supported by a second substrate; and

the at least one modular connection facilitates mechanical and electrical coupling of the first substrate and the second substrate.

27. The illumination apparatus of claim **1**, further comprising the at least one user interface.

28. The illumination apparatus of claim **27**, wherein the at least one user interface comprises at least one external adjustment means.

29. The illumination apparatus of claim **27**, wherein the at least one user interface consists of a single user-operated device to control the at least one controller.

30. The illumination apparatus of claim **27**, wherein:

the at least one controller includes at least one first register associated with the at least one first LED and at least one second register associated with the at least one second LED; and

the at least one user interface and the at least one controller are configured to program the at least one first register and the at least one second register based on the user operation.

31. The illumination apparatus of claim **30**, wherein:

the at least one user interface and the at least one controller are configured to program, based on the user operation, the at least one first register and the at least one second register with intensity values representing duty cycles of PWM control signals.

32. The illumination apparatus of claim **27**, wherein the at least one user interface comprises at least one of at least one potentiometer, a thumb plate, a trackball, a joystick, a switch, and a network interface.

33. The illumination apparatus of claim **1**, further comprising a voltage converter to convert an AC potential to a DC power source to supply DC power to at least the at least one controller.

34. The illumination apparatus of claim **33**, wherein the DC power source supplies DC power to the at least one first LED and the at least one second LED.

35. The illumination apparatus of claim **2**, in combination with a central network controller that is configured to generate the at least one network signal.

36. The illumination apparatus of claim **33**, wherein:

the at least one controller includes a first switch and a second switch respectively associated with the at least one first LED and the at least one second LED; and

the at least one controller is configured to control the at least one first LED and the at least one second LED by turning the first and second switches on and off at high speeds.

37. The illumination apparatus of claim **1**, further comprising a housing to support the at least one controller, the at least one first LED, and the at least one second LED.

38. The illumination apparatus of claim **37**, wherein the housing includes at least one electrically conductive portion.

39. The illumination apparatus of claim 37, wherein the housing includes at least one heat conductive portion.

40. The illumination apparatus of claim 37, wherein the housing includes at least one light diffuser disposed in the path of the first radiation and the second radiation.

41. The illumination apparatus of claim 37, wherein the housing is configured such that the apparatus is a hand-held illumination device.

42. The illumination apparatus of claim 37, wherein the housing is configured such that the apparatus is an underwater swimming pool light.

43. The illumination apparatus of claim 37, wherein the housing is configured such that the at least one controller, the at least one first LED, and the at least one second LED are substantially enclosed by the housing.

44. The illumination apparatus of claim 37, wherein the housing is configured to resemble a conventional light bulb.

45. The illumination apparatus of claim 37, wherein the housing includes at least one power connection coupled to the at least one controller, the at least one power connection configured to engage mechanically and electrically with a conventional light socket.

46. The illumination apparatus of claim 37, further comprising the at least one user interface.

47. The illumination apparatus of claim 46, wherein the at least one user interface is integrated with the housing.

48. The illumination apparatus of claim 2, wherein the addressable controller has an alterable address.

49. The illumination apparatus of claim 2, wherein the at least one network signal is formatted using a DMX protocol, and wherein the addressable controller is configured to control the at least one first LED and the at least one second LED based at least in part on the DMX protocol.

50. The illumination apparatus of claim 2, wherein the addressable controller is configured to control the at least one first LED and the at least one second LED based at least in part on the user operation of the at least one user interface and the lighting information.

51. The illumination apparatus of claim 2, wherein the at least one network signal is provided to the addressable controller based at least in part on the user operation of the at least one user interface.

52. The illumination apparatus of claims 2, wherein the network signal includes address information and lighting information for a plurality of illumination apparatus, wherein the lighting information includes intensity values for LEDs of the plurality of illumination apparatus, and wherein the addressable controller is configured to process the network signal based on an address of the addressable controller and the address information in the network signal to recover from the lighting information the intensity values for at least the first and second LEDs of the illumination apparatus.

53. In an illumination apparatus comprising at least one first LED adapted to output at least first radiation having a first spectrum and at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum, an illumination control method, comprising an act of:

a) independently controlling at least a first intensity of the first radiation and a second intensity of the second radiation in response to user operation of at least one user interface,

wherein the act a) includes an act of:

b) implementing a pulse width modulation (PWM) technique to control at least the first intensity of the first radiation and the second intensity of the second radiation.

54. The illumination method of claim 53, wherein the act a) includes acts of:

a1) receiving at least one addressed network signal including lighting information; and

a2) controlling at least the first intensity and the second intensity based at least in part on the lighting information.

55. The illumination method of claim 54, wherein the act a1) includes an act of:

receiving the at least one addressed network signal based at least in part on the user operation of the at least one user interface.

56. The illumination method of claim 54, wherein the at least one addressed network signal includes address information and lighting information for a plurality of illumination apparatus, wherein the lighting information includes intensity values for LEDs of the plurality of illumination apparatus, wherein the illumination apparatus has an address, and wherein the act a2) includes an act of:

processing the at least one addressed network signal based on the address of the illumination apparatus and the address information in the network signal to recover the intensity values for at least the first and second LEDs of the illumination apparatus.

57. The illumination method of claim 54, wherein the act a1) includes an act of:

receiving the at least one addressed network signal from a central network controller.

58. The illumination method of claim 54, wherein the at least one addressed network signal is formatted using a DMX protocol, and wherein the act a2) includes an act of:

controlling the at least one first LED and the at least one second LED based at least in part on the DMX protocol.

59. The illumination method of claim 53, wherein the act a) includes an act of:

independently controlling at least the first intensity of the first radiation and the second intensity of the second radiation so as to controllably vary an overall color generated by the apparatus as perceived by an observer.

60. The illumination method of claim 53, wherein the act a) includes an act of:

independently controlling at least the first intensity of the first radiation and the second intensity of the second radiation such that an overall color generated by the illumination apparatus represents a single observable color at a given time.

61. The illumination method of claim 53, wherein the act a) includes an act of:

independently controlling at least the first intensity of the first radiation and the second intensity of the second radiation so as to controllably vary an overall intensity of illumination generated by the apparatus as perceived by an observer.

62. The illumination method of claim 53, wherein the act a) includes an act of:

independently controlling at least the first intensity of the first radiation and the second intensity of the second radiation so as to produce a dynamic lighting effect as perceived by an observer.

63. The illumination method of claim 53, wherein the illumination apparatus further comprises at least one third LED adapted to output third radiation having a third spectrum different than the first spectrum and the second spectrum, wherein the act a) includes an act of:

independently controlling a third intensity of the third radiation in response to the user operation of the at least one user interface.

64. The illumination method of claim **63**, wherein at least one of the at least one first LED, the at least one second LED, and the at least one third LED includes at least one blue LED.

65. The illumination method of claim **63**, wherein the at least one first LED, the at least one second LED, and the at least one third LED respectively include at least one red LED, at least one green LED, and at least one blue LED.

66. The illumination method of claim **53**, further comprising an act of:

optically processing at least the first radiation and the second radiation.

67. The illumination method of claim **66**, wherein the act of optically processing includes an act of:

optically processing at least the first and second radiation so as to display a color that is a combination of at least the first and second radiation.

68. The illumination method of claim **53**, wherein the illumination apparatus further includes at least one sensor to monitor at least one detectable condition, and wherein the method further includes an act of:

controlling the at least one first LED and the at least one second LED in response to the at least one detectable condition.

69. The illumination method of claim **53**, further including an act of:

communicating with the illumination apparatus via at least one IR signal or at least one electromagnetic signal.

70. The illumination method of claim **53**, wherein the illumination apparatus includes at least one first register associated with the at least one first LED and at least one second register associated with the at least one second LED, and wherein the act a) includes an act of:

programming the at least one first register and the at least one second register based on the user operation of the at least one user interface.

71. The illumination method of claim **53**, wherein the act a) includes an act of:

variably regulating power to at least one of the at least one first LED and the at least one second LED.

72. The illumination method of claim **53**, wherein each of the at least one first LED and the at least one second LED is associated with a switch, and wherein the act a) includes an act of:

controlling the at least one first LED and the at least one second LED by turning the respective switches on and off at high speeds.

73. The illumination method of claim **58**, wherein each of the at least one first LED and the at least one second LED is associated with a switch, and wherein the act a2) further includes an act of:

controlling the at least one first LED and the at least one second LED by turning the respective switches on and off at high speeds.

74. The illumination method of claim **53**, wherein the act b) includes an act of:

c) implementing the PWM technique such that at least one potentially observable artifact in at least the first radiation and the second radiation is reduced.

75. The illumination method of claim **74**, wherein the at least one potentially observable artifact includes a flicker effect, and wherein the act c) includes an act of:

implementing the PWM technique such that the flicker effect is reduced.

76. The illumination method of claim **75**, wherein the act c) includes an act of:

varying an overall intensity of illumination generated by the apparatus with essentially no perceivable flicker effect.

77. The illumination method of claim **74**, wherein the illumination apparatus includes:

at least one first register associated with the at least one first LED to store a first intensity value representing a first PWM control signal;

at least one second register associated with the at least one second LED to store a second intensity value representing a second PWM control signal; and

at least one PWM counter,

and wherein the act c) includes acts of:

d) programming at least the at least one first register and the at least one second register with the first and second intensity values, respectively, based on the user operation; and

e) generating the first and second PWM control signals based on a comparison of the at least one PWM counter to the first and second intensity values, respectively.

78. The illumination method of claim **77**, wherein the first and second intensity values represent respective duty cycles of the first and second PWM control signals.

79. The illumination method of claim **77**, wherein the act e) includes an act of:

f) freezing the at least one PWM counter when at least one of the at least one first register and the at least one second register is programmed with a new intensity value.

80. The illumination method of claim **79**, wherein the act e) further includes acts of:

g) updating at least one of the first PWM control signal and the second PWM control signal based on the new intensity value after the at least one PWM counter is frozen in the act f); and

h) restarting the at least one PWM counter where it left off after the at least one of the first PWM control signal and the second PWM control signal is updated in the act g).

81. In an illumination apparatus comprising at least one first LED adapted to output at least first radiation having a first spectrum and at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum, an illumination control method, comprising an act of:

a) implementing a pulse width modulation (PWM) technique to control at least the first intensity of the first radiation and the second intensity of the second radiation such that at least one potentially observable artifact in at least the first radiation and the second radiation is reduced.

82. The illumination method of claim **81**, wherein the at least one potentially observable artifact includes a flicker effect, and wherein the act a) includes an act of:

implementing the PWM technique such that the flicker effect is reduced.

83. The illumination method of claim **82**, wherein the act a) includes an act of:

varying an overall intensity of illumination generated by the apparatus with essentially no perceivable flicker effect.

84. The illumination method of claim **81**, wherein the illumination apparatus further includes:

at least one first register associated with the at least one first LED to store a first intensity value representing a first PWM control signal;

at least one second register associated with the at least one second LED to store a second intensity value representing a second PWM control signal; and

at least one PWM counter,

and wherein the act a) includes acts of:

b) programming at least the at least one first register and the at least one second register with the first and second intensity values, respectively; and

c) generating the first and second PWM control signals based on a comparison of the at least one PWM counter to the first and second intensity values, respectively.

85. The illumination method of claim **84**, wherein the first and second intensity values represent respective duty cycles of the first and second PWM control signals.

86. The illumination method of claim **84**, wherein the act c) includes an act of:

d) freezing the at least one PWM counter when at least one of the at least one first register and the at least one second register is programmed with a new intensity value.

87. The illumination method of claim **86**, wherein the act c) further includes acts of:

e) updating at least one of the first PWM control signal and the second PWM control signal based on the new intensity value after the at least one PWM counter is frozen in the act d); and

f) restarting the at least one PWM counter where it left off after the at least one of the first PWM control signal and the second PWM control signal is updated in the act e).

88. An illumination apparatus, comprising:

at least one first LED adapted to output at least first radiation having a first spectrum;

at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum;

at least one controller coupled to the at least one first LED and the at least one second LED and configured to respond to user operation of at least one user interface in communication with the at least one controller, the at least one controller further configured to independently control at least a first intensity of the first radiation and a second intensity of the second radiation in response to the user operation; and

at least one sensor to monitor at least one detectable condition,

wherein the at least one controller is configured to further control the at least one first LED and the at least one second LED in response to the at least one detectable condition.

89. An illumination apparatus, comprising:

at least one first LED adapted to output at least first radiation having a first spectrum;

at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum;

at least one controller coupled to the at least one first LED and the at least one second LED and configured to respond to user operation of at least one user interface in communication with the at least one controller, the at least one controller further configured to independently control at least a first intensity of the first radiation and a second intensity of the second radiation in response to the user operation; and

at least one transceiver coupled to the at least one controller and configured to communicate at least one IR signal or at least one electromagnetic signal.

90. An illumination apparatus, comprising:

at least one first LED adapted to output at least first radiation having a first spectrum;

at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum; and

at least one controller coupled to the at least one first LED and the at least one second LED and configured to respond to user operation of at least one user interface in communication with the at least one controller, the at least one controller further configured to independently control at least a first intensity of the first radiation and a second intensity of the second radiation in response to the user operation,

wherein:

the at least one controller includes at least one first register associated with the at least one first LED and at least one second register associated with the at least one second LED; and

the at least one controller is configured to program the at least one first register and the at least one second register based on the user operation.

91. An illumination apparatus, comprising:

at least one first LED adapted to output at least first radiation having a first spectrum;

at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum; and

at least one controller coupled to the at least one first LED and the at least one second LED and configured to respond to user operation of at least one user interface in communication with the at least one controller, the at least one controller further configured to independently control at least a first intensity of the first radiation and a second intensity of the second radiation in response to the user operation,

wherein the at least one controller includes at least one adjustable regulator configured to variably regulate power to at least one of the at least one first LED and the at least one second LED.

92. An illumination apparatus, comprising:

at least one first LED adapted to output at least first radiation having a first spectrum;

at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum; and

at least one controller coupled to the at least one first LED and the at least one second LED and configured to respond to user operation of at least one user interface in communication with the at least one controller, the at least one controller further configured to independently control at least a first intensity of the first radiation and a second intensity of the second radiation in response to the user operation,

wherein:

the at least one controller includes a first switch and a second switch respectively associated with the at least one first LED and the at least one second LED; and

the at least one controller is configured to control the at least one first LED and the at least one second LED by turning the first and second switches on and off at high speeds.

93. In an illumination apparatus comprising at least one first LED adapted to output at least first radiation having a

first spectrum and at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum, an illumination control method, comprising acts of:

a) receiving at least one signal formatted at least in part using a DMX protocol and including lighting information based at least in part on user operation of at least one user interface; and

b) controlling at least the first intensity and the second intensity based at least in part on the lighting information.

94. The illumination method of claim **93**, wherein the at least one user interface includes a central network controller, and wherein the act a) includes an act of:

receiving the at least one signal from the central network controller.

95. The illumination method of claim **93**, wherein the act a) includes an act of:

a1) receiving at least one network signal formatted at least in part using the DMX protocol and including lighting information for a plurality of illumination apparatus.

96. The illumination method of claim **95**, wherein the act a1) includes an act of:

receiving the at least one network signal based at least in part on the user operation of the at least one user interface.

97. The illumination method of claim **95**, wherein the at least one network signal includes address information, wherein the lighting information includes intensity values for LEDs of the plurality of illumination apparatus, wherein the illumination apparatus has an address, and wherein the act a1) includes an act of:

a2) processing the at least one network signal based on the address of the illumination apparatus and the address information in the at least one network signal to recover the intensity values for at least the first and second LEDs of the illumination apparatus.

98. The illumination method of claim **97**, wherein the address information relates to an arrangement of data packets in the at least one network signal, and wherein the act a2) includes an act of:

processing the at least one network signal based on the address of the illumination apparatus and the arrangement of data packets in the at least one network signal to recover the intensity values for at least the first and second LEDs of the illumination apparatus.

99. The illumination method of claim **97**, wherein the at least one user interface includes a central network controller, and wherein the act a) includes an act of:

receiving the at least one signal from the central network controller.

100. The illumination method of claim **93**, wherein the act b) further includes an act of:

implementing a pulse width modulation technique to control at least the first intensity of the first radiation and the second intensity of the second radiation.

101. The illumination method of claim **93**, wherein each of the at least one first LED and the at least one second LED is associated with a switch, and wherein the act a) further includes an act of:

controlling the at least one first LED and the at least one second LED by turning the respective switches on and off at high speeds.

102. An illumination apparatus, comprising:

at least one first LED adapted to output at least first radiation having a first spectrum;

at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum;

at least one user interface; and

at least one controller coupled to the at least one first LED and the at least one second LED and configured to respond to user operation of the at least one user interface, the at least one controller further configured to independently control at least a first intensity of the first radiation and a second intensity of the second radiation in response to the user operation,

wherein the at least one user interface comprises at least one external adjustment means.

103. An illumination apparatus, comprising:

at least one first LED adapted to output at least first radiation having a first spectrum;

at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum; and

at least one controller coupled to the at least one first LED and the at least one second LED and configured to respond to user operation of at least one user interface in communication with the at least one controller, the at least one controller further configured to independently control at least a first intensity of the first radiation and a second intensity of the second radiation in response to the user operation,

wherein the at least one controller is configured as an addressable controller capable of receiving at least one network signal including lighting information for a plurality of illumination apparatus.

104. The illumination apparatus of claim **103**, wherein the addressable controller is configured to control the at least one first LED and the at least one second LED based at least in part on the user operation of the at least one user interface and the lighting information.

105. The illumination apparatus of claim **103**, wherein the at least one network signal is provided to the addressable controller based at least in part on the user operation of the at least one user interface.

106. The illumination apparatus of claim **103**, wherein the lighting information includes intensity values for LEDs of the plurality of illumination apparatus, and wherein the addressable controller is configured to process the at least one network signal based on an address of the addressable controller to recover from the lighting information the intensity values for at least the first and second LEDs of the illumination apparatus.

107. The illumination apparatus of claim **106**, wherein the at least one network signal includes address information.

108. The illumination apparatus of claim **107**, wherein the address information relates to an arrangement of data packets in the at least one network signal.

109. The illumination apparatus of claim **103**, wherein the addressable controller has an alterable address.

110. The illumination apparatus of claim **103**, wherein the at least one network signal is formatted using a DMX protocol, and wherein the addressable controller is configured to control the at least one first LED and the at least one second LED based at least in part on the DMX protocol.

111. The illumination apparatus of claim **103**, in combination with the at least one user interface, wherein the at least one user interface is a central network controller that is configured to generate the at least one network signal.

112. The illumination apparatus of claim **103**, wherein the addressable controller is configured to implement a pulse

width modulation technique to control at least the first intensity of the first radiation and the second intensity of the second radiation.

113. The illumination apparatus of claim **103**, wherein:

the addressable controller includes a first switch and a second switch respectively associated with the at least one first LED and the at least one second LED; and

the addressable controller is configured to control the at least one first LED and the at least one second LED by turning the first and second switches on and off at high speeds.

114. The illumination apparatus of claim **103**, further including at least one modular connection to facilitate coupling of the at least one controller to the at least one first LED and the at least one second LED.

115. The illumination apparatus of claim **103**, further including at least one modular connection to facilitate coupling of the at least one controller to the at least one first LED and the at least one second LED.

116. The illumination apparatus of claim **115**, wherein:

the at least one first LED and the at least one second LED are supported by a first substrate;

the at least one controller is supported by a second substrate; and the at least one modular connection is configured to facilitate at least one of a mechanical coupling and an electrical coupling of the first substrate and the second substrate.

117. In an illumination apparatus comprising at least one first LED adapted to output at least first radiation having a first spectrum, at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum, and at least one sensor to monitor at least one detectable condition, an illumination control method, comprising acts of:

independently controlling at least a first intensity of the first radiation and a second intensity of the second radiation in response to user operation of at least one user interface; and

controlling the at least one first LED and the at least one second LED in response to the at least one detectable condition.

118. In an illumination apparatus comprising at least one first LED adapted to output at least first radiation having a first spectrum and at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum, an illumination control method, comprising acts of:

independently controlling at least a first intensity of the first radiation and a second intensity of the second radiation in response to user operation of at least one user interface; and

communicating with the illumination apparatus via at least one IR signal or at least one electromagnetic signal.

119. In an illumination apparatus comprising at least one first LED adapted to output at least first radiation having a first spectrum and at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum, an illumination control method, comprising an act of:

a) independently controlling at least a first intensity of the first radiation and a second intensity of the second radiation in response to user operation of at least one user interface, wherein the illumination apparatus includes at least one first register associated with the at least one first LED and at least one second register associated with the at least one second LED, and wherein the act a) includes an act of:

programming the at least one first register and the at least one second register based on the user operation of the at least one user interface.

120. In an illumination apparatus comprising at least one first LED adapted to output at least first radiation having a first spectrum and at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum, an illumination control method, comprising acts of:

independently controlling at least a first intensity of the first radiation and a second intensity of the second radiation in response to user operation of at least one user interface; and

variably regulating power to at least one of the at least one first LED and the at least one second LED.

121. In an illumination apparatus comprising at least one first LED adapted to output at least first radiation having a first spectrum and at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum, an illumination control method, comprising an act of:

a) independently controlling at least a first intensity of the first radiation and a second intensity of the second radiation in response to user operation of at least one user interface, wherein each of the at least one first LED and the at least one second LED is associated with a switch, and wherein the act a) includes an act of:

controlling the at least one first LED and the at least one second LED by turning the respective switches on and off at high speeds.

122. In an illumination apparatus comprising at least one first LED adapted to output at least first radiation having a first spectrum and at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum, an illumination control method, comprising an act of:

a) independently controlling at least a first intensity of the first radiation and a second intensity of the second radiation in response to user operation of at least one user interface, wherein the act a) includes acts of:

a1) receiving at least one network signal including lighting information; and

a2) controlling at least the first intensity and the second intensity based at least in part on the lighting information.

123. The illumination method of claim **122**, wherein the act a1) includes an act of:

receiving the at least one network signal based at least in part on the user operation of the at least one user interface.

124. The illumination method of claim **122**, wherein the at least one network signal includes address information and lighting information for a plurality of illumination apparatus, wherein the lighting information includes intensity values for LEDs of the plurality of illumination apparatus, wherein the illumination apparatus has an address, and wherein the act a2) includes an act of:

a3) processing the at least one network signal based on the address of the illumination apparatus and the address information in the at least one network signal to recover the intensity values for at least the first and second LEDs of the illumination apparatus.

125. The illumination method of claim **124**, wherein the address information relates to an arrangement of data pack-

ets in the at least one network signal, and wherein the act a3) includes an act of:

processing the at least one network signal based on the address of the illumination apparatus and the arrangement of data packets in the at least one network signal to recover the intensity values for at least the first and second LEDs of the illumination apparatus.

126. The illumination method of claim **122**, wherein the at least one user interface includes a central network controller, and wherein the act a1) includes an act of: receiving the at least one network signal from the central network controller.

127. The illumination method of claim **122**, wherein the at least one network signal is formatted using a DMX protocol, and wherein the act a2) includes an act of:

controlling the at least one first LED and the at least one second LED based at least in part on the DMX protocol.

128. The illumination method of claim **122**, wherein the act a2) further includes an act of:

implementing a pulse width modulation technique to control at least the first intensity of the first radiation and the second intensity of the second radiation.

129. The illumination method of claim **122**, wherein each of the at least one first LED and the at least one second LED is associated with a switch, and wherein the act a2) further includes an act of:

controlling the at least one first LED and the at least one second LED by turning the respective switches on and off at high speeds.

130. An illumination apparatus, comprising:

at least one first LED adapted to output at least first radiation having a first spectrum;

at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum; and

at least one controller coupled to the at least one first LED and the at least one second LED and configured to respond to at least one signal formatted at least in part using a DMX protocol, the at least one signal including lighting information based at least in part on user operation of at least one user interface in communication with the at least one controller, the at least one controller further configured to independently control at least a first intensity of the first radiation and a second intensity of the second radiation in response to the lighting information.

131. The apparatus of claim **130**, in combination with the at least one user interface.

132. The combination of claim **131**, wherein the at least one user interface includes a central network controller.

133. The illumination apparatus of claim **130**, further including at least one modular connection to facilitate coupling of the at least one controller to the at least one first LED and the at least one second LED.

134. The illumination apparatus of claim **133**, wherein:

the at least one first LED and the at least one second LED are supported by a first substrate;

the at least one controller is supported by a second substrate; and

the at least one modular connection is configured to facilitate at least one of a mechanical coupling and an electrical coupling of the first substrate and the second substrate.

135. The illumination apparatus of claim **130**, wherein the at least one controller further is configured as an addressable controller capable of receiving the at least one signal as at least one network signal including lighting information for a plurality of illumination apparatus.

136. The illumination apparatus of claim **135**, wherein the lighting information includes intensity values for LEDs of the plurality of illumination apparatus, and wherein the addressable controller is configured to process the at least one network signal based on an address of the addressable controller to recover from the lighting information the intensity values for at least the first and second LEDs of the illumination apparatus.

137. The illumination apparatus of claim **136**, wherein the at least one network signal includes address information.

138. The illumination apparatus of claim **137**, wherein the address information relates to an arrangement of data packets in the at least one network signal.

139. The illumination apparatus of claim **136**, wherein the addressable controller has an alterable address.

140. The illumination apparatus of claim **136**, in combination with the at least one user interface, wherein the at least one user interface is a central network controller that is configured to generate the at least one network signal.

141. The illumination apparatus of claim **130**, wherein the at least one controller is configured to implement a pulse width modulation technique to control at least the first intensity of the first radiation and the second intensity of the second radiation.

142. The illumination apparatus of claim **130**, wherein:

the at least one controller includes a first switch and a second switch respectively associated with the at least one first LED and the at least one second LED; and

the at least one controller is configured to control the at least one first LED and the at least one second LED by turning the first and second switches on and off at high speeds.

143. An illumination apparatus, comprising:

at least one first LED adapted to output at least first radiation having a first spectrum;

at least one second LED adapted to output second radiation having a second spectrum different than the first spectrum;

at least one controller coupled to the at least one first LED and the at least one second LED and configured to respond to user operation of at least one user interface in communication with the at least one controller, the at least one controller further configured to independently control at least a first intensity of the first radiation and a second intensity of the second radiation in response to the user operation; and

at least one modular connection to facilitate coupling of the at least one controller to the at least one first LED and the at least one second LED.

144. The illumination apparatus of claim **143**, wherein:

the at least one first LED and the at least one second LED are supported by a first substrate;

the at least one controller is supported by a second substrate; and

the at least one modular connection is configured to facilitate at least one of a mechanical coupling and an electrical coupling of the first substrate and the second substrate.

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UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 6,788,011 B2
DATED : September 7, 2004
INVENTOR(S) : George G. Mueller and Ihor A. Lys

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title page,
Item [56], **References Cited**, U.S. PATENT DOCUMENTS, please add the following:

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UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,788,011 B2
DATED : September 7, 2004
INVENTOR(S) : George G. Mueller and Ihor A. Lys

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title page (cont'd),

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Drawings,
Fig. 8, please add the reference numeral -- 92 --.

Column 7,
Line 57, please replace "dug" with -- duty --

Signed and Sealed this

Twenty-third Day of November, 2004

Jon W. Dudas

JON W. DUDAS
Director of the United States Patent and Trademark Office

US006806659B1

(12) **United States Patent**
Mueller et al.

(10) **Patent No.: US 6,806,659 B1**
(45) **Date of Patent: *Oct. 19, 2004**

(54) **MULTICOLORED LED LIGHTING METHOD AND APPARATUS**

(75) Inventors: **George G. Mueller**, Boston, MA (US); **Ihor Lys**, Boston, MA (US)

(73) Assignee: **Color Kinetics, Incorporated**, Boston, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **09/669,121**

(22) Filed: **Sep. 25, 2000**

Related U.S. Application Data

(63) Continuation of application No. 09/425,770, filed on Oct. 22, 1999, now Pat. No. 6,150,774, which is a continuation of application No. 08/920,156, filed on Aug. 26, 1997, now Pat. No. 6,016,038.

(51) **Int. Cl.**[7] **G05F 1/00**

(52) **U.S. Cl.** **315/295**; 315/315; 315/360; 315/362

(58) **Field of Search** 315/291, 292, 315/295, 300, 302, 308, 315, 360, 362, 76, 324

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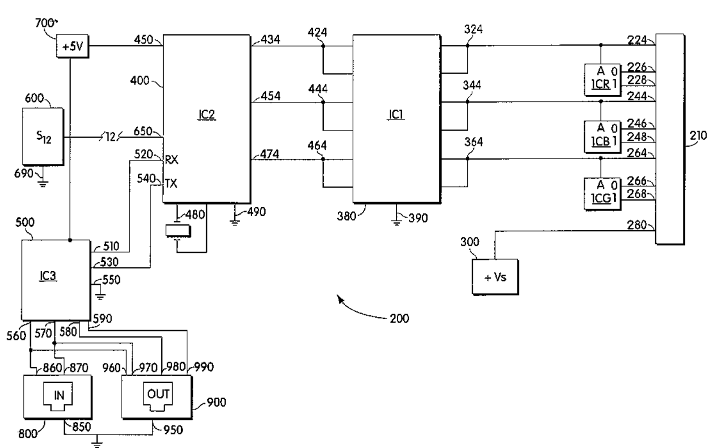
(57) **ABSTRACT**

Illumination apparatus and networks of the same including a number of different embodiments. In one embodiment, the illumination apparatus comprises a plurality of LEDs including at least two different colors; a switching device, interposed between the LEDs and a common potential reference, including at least two switches corresponding to current paths of the two different color LEDs; a controller that opens and closes the switches according to a predetermined duty cycle; and a hand-held housing with a compartment for containing a power source and the common reference potential, as well as a lens assembly for reflecting light from the LEDs. Another embodiment is directed to a lighting network including a controller and a plurality of uniquely-addressable illumination units, each including two different color LEDs. Each illumination unit includes a network interface that receives from the controller data comprising LED intensity values, a memory that stores the intensity values, a controller that generates pulse width modulated signals having duty cycles corresponding to the intensity values and a switch that directs current to the LEDs based on the pulse width modulated signals.

26 Claims, 6 Drawing Sheets



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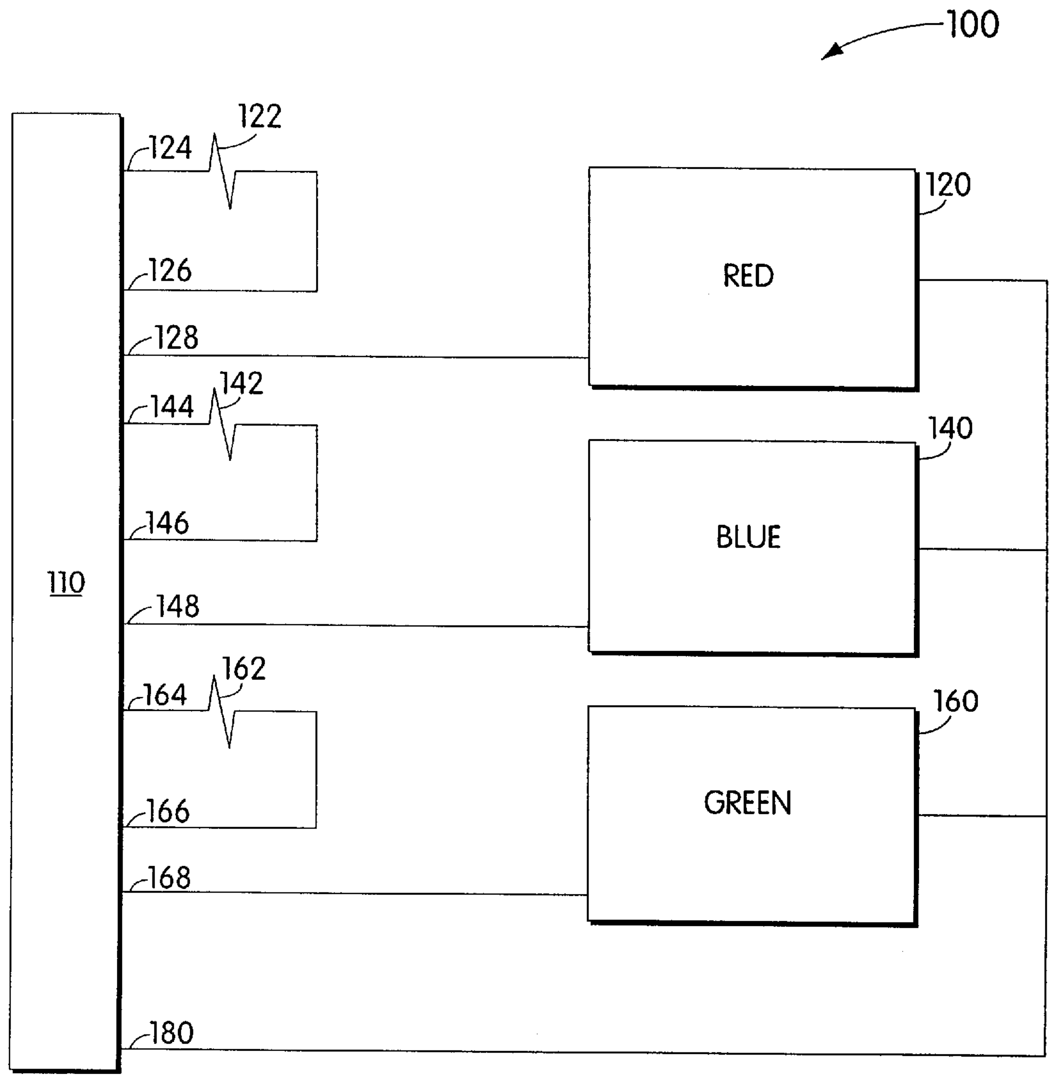
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GREEN
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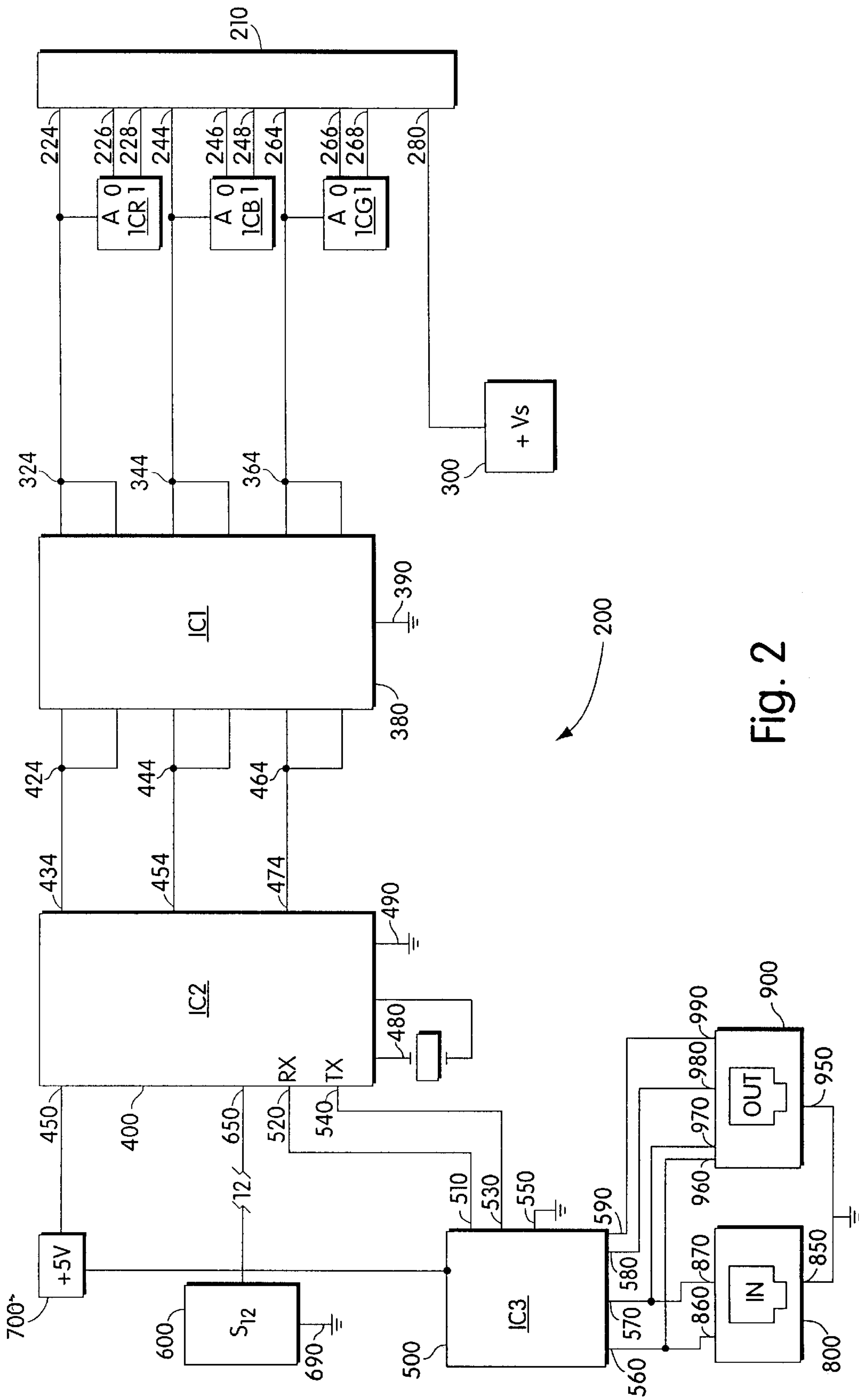
Fig. 1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+Vs
300
324
344
364
IC1
390
380
200
424
444
464
434
454
474
IC2
490
480
RX
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12
+5V
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500
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Fig. 2

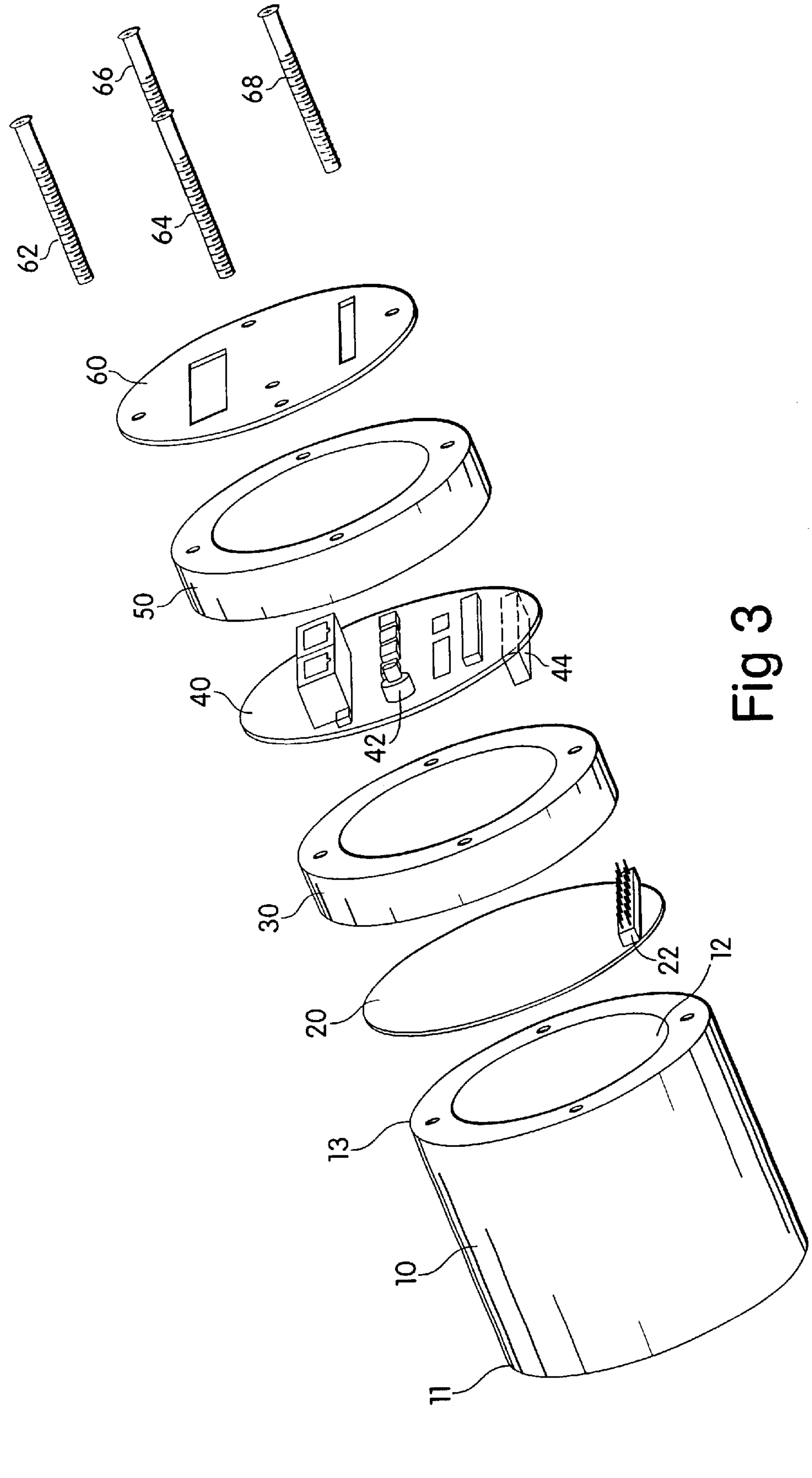


Fig 3

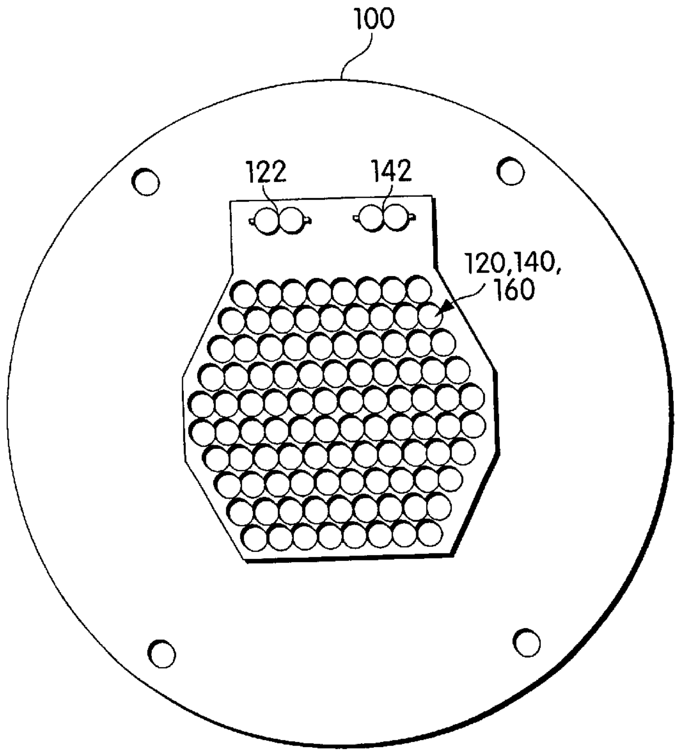


Fig. 4

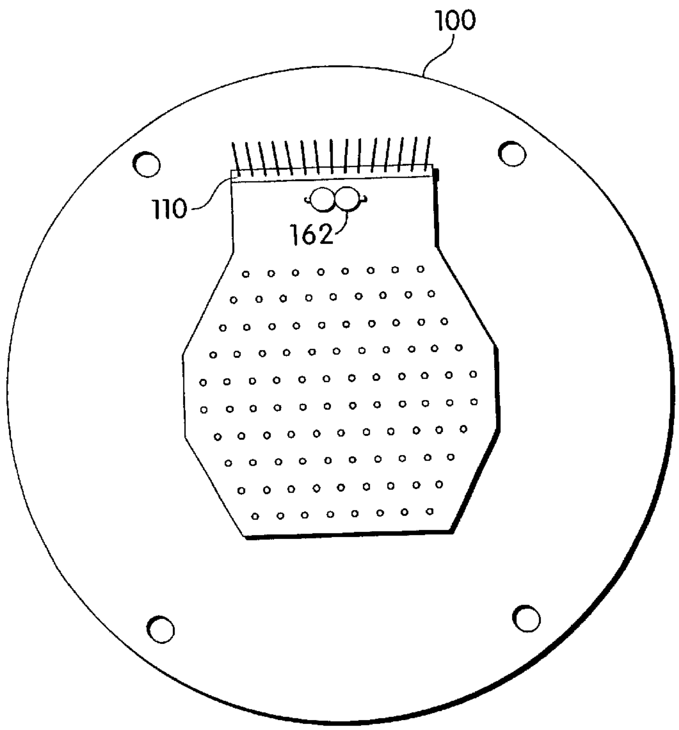
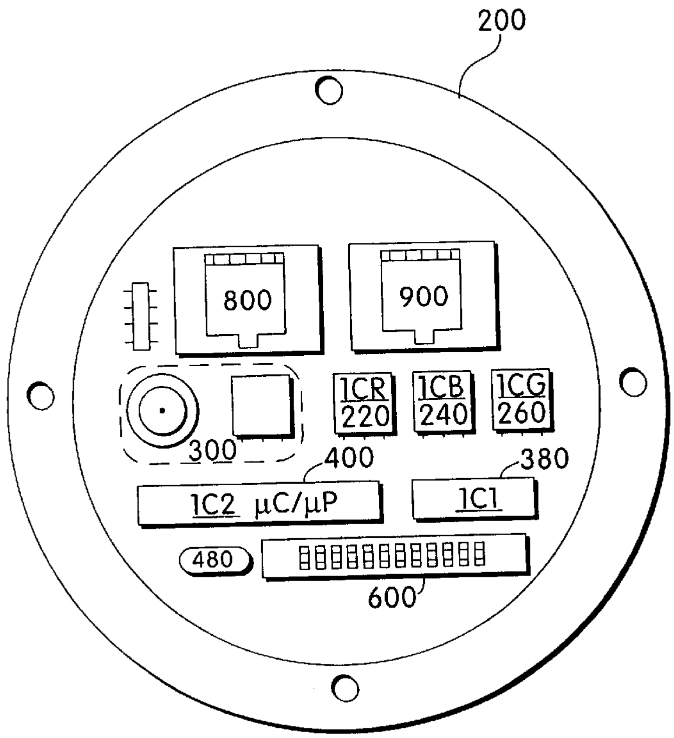


Fig. 5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1CB
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1CG
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300
400
380
1C2 μC/μP
1C1
480
600

Fig. 6

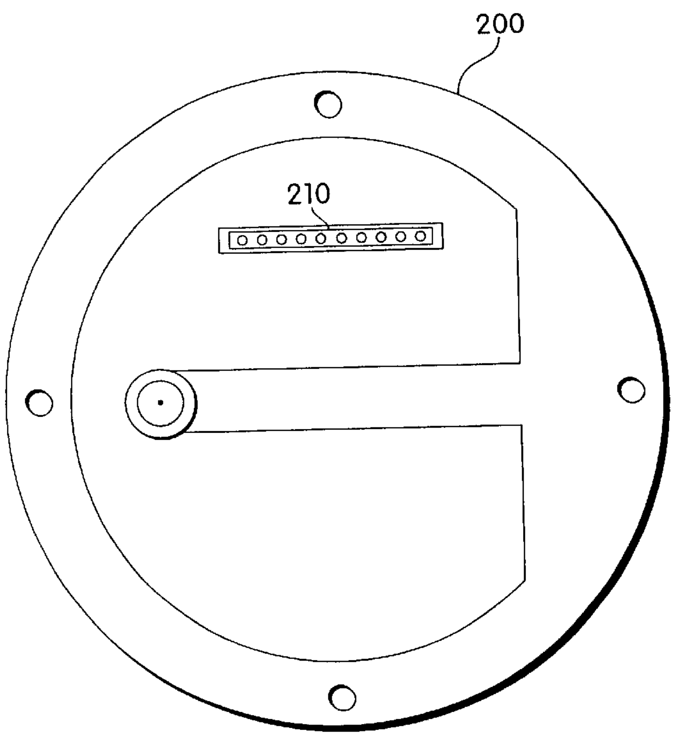
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Fig. 7

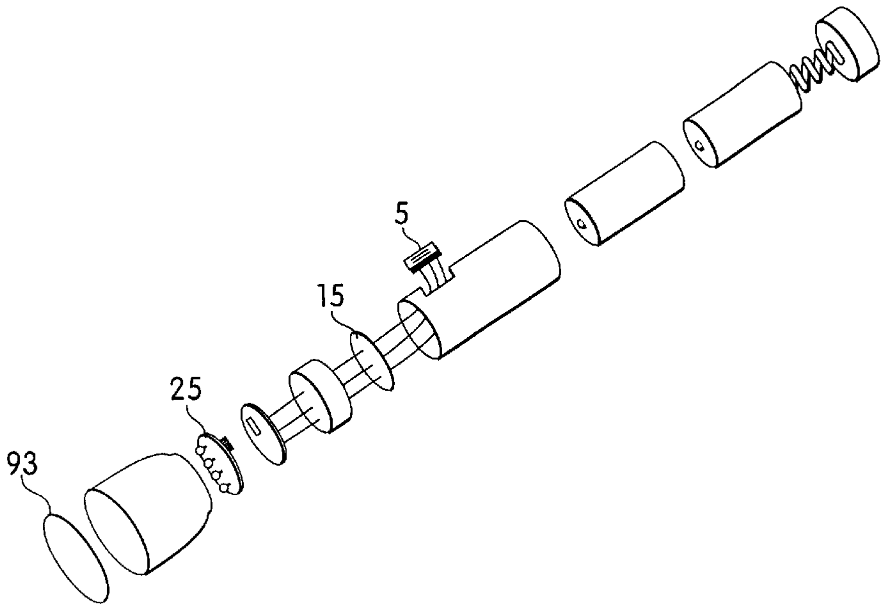
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Fig. 8

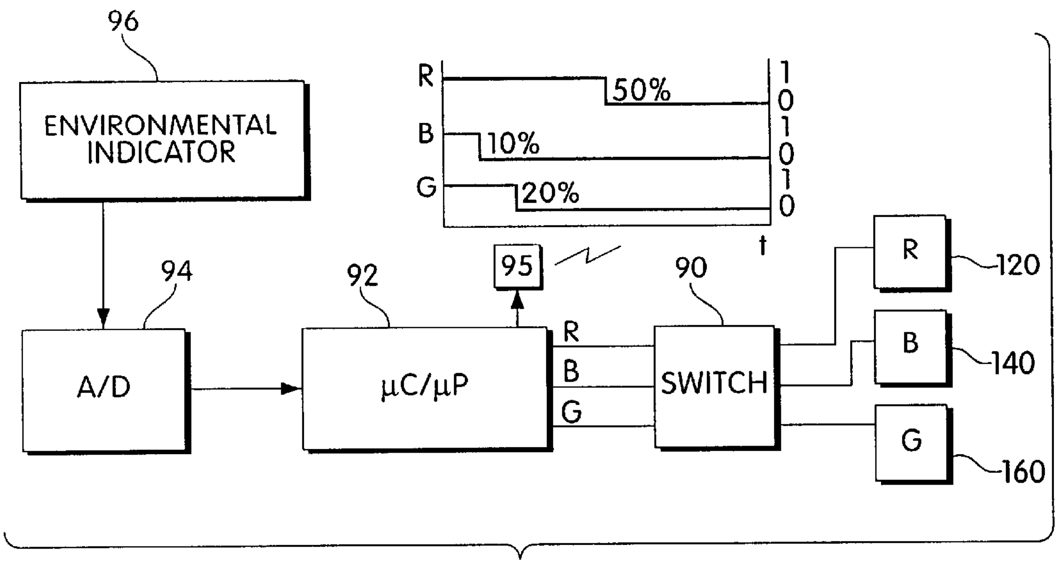
96
ENVIRONMENTAL INDICATOR
94
A/D
92
μC/μP
95
90
SWITCH
R
B
G
50%
10%
20%
1
0
t
R
120
B
140
G
160

Fig. 9

MULTICOLORED LED LIGHTING METHOD AND APPARATUS

This application is a continuation of U.S. application Ser. No. 09/425,770 filed on Oct. 22, 1999, now U.S. Pat. No. 6,150,774, which is a continuation of U.S. application Ser. No. 08/920,156 filed on Aug. 26, 1997, now U.S. Pat. No. 6,016,038.

BACKGROUND OF THE INVENTION

The present invention relates to providing light of a selectable color using LEDs. More particularly, the present invention is a method and apparatus for providing multicolored illumination More particularly still, the present invention is an apparatus for providing a computer controlled multicolored illumination network capable of high performance and rapid color selection and change.

It is well known that combining the projected light of one color with the projected light of another color will result in the creation of a third color. It is also well known that the three most commonly used primary colors—red, blue and green—can be combined in different proportions to generate almost any color in the visible spectrum. The present invention takes advantage of these effects by combining the projected light from at least two light emitting diodes (LEDs) of different primary colors.

Computer lighting networks are not new. U.S. Pat. No. 5,420,482, issued to Phares, describes one such network that uses different colored LEDs to generate a selectable color. Phares is primarily for use as a display apparatus. However, the apparatus has several disadvantages and limitations. First, each of the three color LEDs in Phares is powered through a transistor biasing scheme in which the transistor base is coupled to a respective latch register through biasing resistors. The three latches are all simultaneously connected to the same data lines on the data bus. This means it is impossible in Phares to change all three LED transistor biases independently and simultaneously. Also, biasing of the transistors is inefficient because power delivered to the LEDs is smaller than that dissipated in the biasing network. This makes the device poorly suited for efficient illumination applications. The transistor biasing used by Phares also makes it difficult, if not impossible, to interchange groups of LEDs having different power ratings, and hence different intensity levels.

U.S. Pat. No. 4,845,481, issued to Havel, is directed to a multicolored display device. Havel addresses some, but not all of the switching problems associated with Phares. Havel uses a pulse width modulated signal to provide current to respective LEDs at a particular duty cycle. However, no provision is made for precise and rapid control over the colors emitted. As a stand alone unit, the apparatus in Havel suggests away from network lighting, and therefore lacks any teaching as to how to implement a pulse width modulated computer lighting network. Further, Havel does not appreciate the use of LEDs beyond mere displays, such as for illumination.

U.S. Pat. No. 5,184,114, issued to Brown, shows an LED display system. But Brown lacks any suggestion to use LEDs for illumination, or to use LEDs in a configurable computer network environment. U.S. Pat. No. 5,134,387, issued to Smith et al., directed to an LED matrix display, contains similar problems. Its rudimentary current control scheme severely limits the possible range of colors that can be displayed.

It is an object of the present invention to overcome the limitations of the prior art by providing a high performance computer controlled multicolored LED lighting network.

It is a further object of the present invention to provide a unique LED lighting network structure capable of both a linear chain of nodes and a binary tree configuration.

It is still another object of the present invention to provide a unique heat-dissipating housing to contain the lighting units of the lighting network.

It is yet another object of the present invention to provide a current regulated LED lighting apparatus, wherein the apparatus contains lighting modules each having its own maximum current rating and each conveniently interchangeable with one another.

It is a still further object of the present invention to provide a unique computer current-controlled LED lighting assembly for use as a general illumination device capable of emitting multiple colors in a continuously programmable 24-bit spectrum.

It is yet a still further object of the present invention to provide a unique flashlight, inclinometer, thermometer, general environmental indicator and lightbulb, all utilizing the general computer current-control principles of the present invention.

Other objects of the present invention will be apparent from the detailed description below.

SUMMARY OF THE INVENTION

In brief, the invention herein comprises a pulse width modulated current control for an LED lighting assembly, where each current-controlled unit is uniquely addressable and capable of receiving illumination color information on a computer lighting network. In a further embodiment, the invention includes a binary tree network configuration of lighting units (nodes). In another embodiment, the present invention comprises a heat dissipating housing, made out of a heat-conductive material, for housing the lighting assembly. The heat dissipating housing contains two stacked circuit boards holding respectively the power module and the light module. The light module is adapted to be conveniently interchanged with other light modules having programmable current, and hence maximum light intensity, ratings. Other embodiments of the present invention involve novel applications for the general principles described herein.

DESCRIPTION OF THE DRAWINGS

FIG. **1** is a stylized electrical circuit schematic of the light module of the present invention.

FIG. **2** is a stylized electrical circuit schematic of the power module of the present invention.

FIG. **3** is an exploded view of the housing of one of the embodiments of the present invention.

FIG. **4** is a plan view of the LED-containing side of the light module of the present invention.

FIG. **5** is a plan view of the electrical connector side of the light module of the present invention.

FIG. **6** is a plan view of the power terminal side of the power module of the present invention.

FIG. **7** is a plan view of the electrical connector side of the power module of the present invention.

FIG. **8** is an exploded view of a flashlight assembly containing the LED lighting module of the present invention.

FIG. **9** is a control block diagram of the environmental indicator of the present invention.

DETAILED DESCRIPTION

The structure and operation of a preferred embodiment will now be described. It should be understood that many

other ways of practicing the inventions herein are available, and the embodiments described herein are exemplary and not limiting. Turning to FIG. **1**, shown is an electrical schematic representation of a light module **100** of the present invention FIGS. **4** and **5** show the LED-containing side and the electrical connector side of light module **100**. Light module **100** is self-contained, and is configured to be a standard item interchangeable with any similarly constructed light module. Light module **100** contains a ten-pin electrical connector **110** of the general type. In this embodiment, the connector **110** contains male pins adapted to fit into a complementary ten-pin connector female assembly, to be described below. Pin **180** is the power supply. A source of DC electrical potential enters module **100** on pin **180**. Pin **180** is electrically connected to the anode end of light emitting diode (LED) sets **120**, **140** and **160** to establish a uniform high potential on each anode end.

LED set **120** contains red LEDs, set **140** contains blue and set **160** contains green, each obtainable from the Nichia America Corporation. These LEDs are primary colors, in the sense that such colors when combined in preselected proportions can generate any color in the spectrum. While three primary colors is preferred, it will be understood that the present invention will function nearly as well with only two primary colors to generate any color in the spectrum. Likewise, while the different primary colors are arranged herein on sets of uniformly colored LEDs, it will be appreciated that the same effect may be achieved with single LEDs containing multiple color-emitting semiconductor dies. LED sets **120**, **140** and **160** each preferably contains a serial/parallel array of LEDs in the manner described by Okuno in U.S. Pat. No. 4,298,869, incorporated herein by reference. In the present embodiment, LED set **120** contains three parallel connected rows of nine red LEDs (not shown), and LED sets **140** and **160** each contain five parallel connected rows of five blue and green LEDs, respectively (not shown). It is understood by those in the art that, in general, each red LED drops the potential in the line by a lower amount than each blue or green LED, about 2.1 V, compared to 4.0 V, respectively, which accounts for the different row lengths. This is because the number of LEDs in each row is determined by the amount of voltage drop desired between the anode end at the power supply voltage and the cathode end of the last LED in the row. Also, the parallel arrangement of rows is a fail-safe measure that ensures that the light module **100** will still function even if a single LED in a row fails, thus opening the electrical circuit in that row. The cathode ends of the three parallel rows of nine red LEDs in LED set **120** are then connected in common, and go to pin **128** on connector **110**. Likewise, the cathode ends of the five parallel rows of five blue LEDs in LED set **140** are connected in common, and go to pin **148** on connector **110**. The cathode ends of the five parallel rows of five green LEDs in LED set **160** are connected in common, and go to pin **168** on connector **110**. Finally, on light module **100**, each LED set is associated with a programming resistor that combines with other components, described below, to program the maximum current through each set of LEDs. Between pin **124** and **126** is resistor **122**, 6.2Ω. Between pin **144** and **146** is resistor **142**, 4.7Ω. Between pin **164** and **166** is resistor **162**, 4.7Ω. Resistor **122** programs maximum current through red LED set **120**, resistor **142** programs maximum current through blue LED set **140**, and resistor **162** programs maximum current through green LED set **160**. The values these resistors should take are determined empirically, based on the desired maximum light intensity of each LED set. In the present embodiment, the resistances above program red, blue and green currents of 70, 50 and 50 μA, respectively.

With the electrical structure of light module **100** described, attention will now be given to the electrical structure of power module **200**, shown in FIG. **2**. FIGS. **6** and **7** show the power terminal side and electrical connector side of an embodiment of power module **200**. Like light module **100**, power module **200** is self contained. Interconnection with male pin set **110** is achieved through complementary female pin set **210**. Pin **280** connects with pin **180** for supplying power, delivered to pin **280** from supply **300**. Supply **300** is shown as a functional block for simplicity. In actuality, supply **300** can take numerous forms for generating a DC voltage. In the present embodiment, supply **300** provides 24 Volts through a connection terminal (not shown), coupled to pin **280** through transient protection capacitors (not shown) of the general type. It will be appreciated that supply **300** may also supply a DC voltage after rectification and/or voltage transformation of an AC supply, as described more fully in U.S. Pat. No. 4,298,869.

Also connected to pin connector **210** are three current programming integrated circuits, ICR **220**, ICB **240** and ICG **260**. Each of these is a three terminal adjustable regulator, preferably part number LM317B, available from the National Semiconductor Corporation, Santa Clara, Calif. The teachings of the LM317 datasheet are incorporated herein by reference. Each regulator contains an input terminal, an output terminal and an adjustment terminal, labeled I, O and A, respectively. The regulators function to maintain a constant maximum current into the input terminal and out of the output terminal. This maximum current is pre-programmed by setting a resistance between the output and the adjustment terminals. This is because the regulator will cause the voltage at the input terminal to settle to whatever value is needed to cause 1.25 V to appear across the fixed current set resistor, thus causing constant current to flow. Since each functions identically, only ICR **220** will now be described. First, current enters the input terminal of ICR **220** from pin **228**. Of course, pin **228** in the power module is coupled to pin **128** in the light module, and receives current directly from the cathode end of the red LED set **120**. Since resistor **122** is ordinarily disposed between the output and adjustment terminals of ICR **220** through pins **224**/**124** and **226**/**126**, resistor **122** programs the amount of current regulated by ICR **220**. Eventually, the current output from the adjustment terminal of ICR **220** enters a Darlington driver. In this way, ICR **220** and associated resistor **122** program the maximum current through red LED set **120**. Similar results are achieved with ICB **240** and resistor **142** for blue LED set **140**, and with ICG **260** and resistor **162** for green LED set **160**.

The red, blue and green LED currents enter another integrated circuit, IC1 **380**, at respective nodes **324**, **344** and **364**. IC1 **380** is preferably a high current/voltage Darlington driver, part no. DS2003 available from the National Semiconductor Corporation, Santa Clara, Calif. IC1 **380** is used as a current sink, and functions to switch current between respective LED sets and ground **390**. As described in the DS2003 datasheet, incorporated herein by reference. IC1 contains six sets of Darlington transistors with appropriate on-board biasing resistors. As shown, nodes **324**, **344** and **364** couple the current from the respective LED sets to three pairs of these Darlington transistors, in the well known manner to take advantage of the fact that the current rating of IC1 **380** may be doubled by using pairs of Darlington transistors to sink respective currents. Each of the three on-board Darlington pairs is used in the following manner as a switch. The base of each Darlington pair is coupled to signal inputs **424**, **444** and **464**, respectively. Hence, input

424 is the signal input for switching current through node 324, and thus the red LED set 120. Input 444 is the signal input for switching current though node 344, and thus the blue LED set 140. Input 464 is the signal input for switching current through node 364, and thus the green LED set 160. Signal inputs 424, 444 and 464 are coupled to respective signal outputs 434, 454 and 474 on microcontroller IC2 400, as described below. In essence, when a high frequency square wave is incident on a respective signal input, IC1 380 switches current through a respective node with the identical frequency and duty cycle. Thus, in operation, the states of signal inputs 424, 444 and 464 directly correlate with the opening and closing of the power circuit through respective LED sets 120, 140 and 160.

The structure and operation of microcontroller IC2 400 will now be described. Microcontroller IC2 400 is preferably a MICROCHIP brand PIC16C63, although almost any properly programmed microcontroller or microprocessor can perform the software functions described herein. The main function of microcontroller IC2 400 is to convert numerical data received on serial Rx pin 520 into three independent high frequency square waves of uniform frequency but independent duty cycles on signal output pins 434, 454 and 474. The FIG. 2 representation of microcontroller IC2 400 is partially stylized, in that persons of skill in the art will appreciate that certain of the twenty-eight standard pins have been omitted or combined for greatest clarity.

Microcontroller IC2 400 is powered through pin 450, which is coupled to a 5 Volt source of DC power 700. Source 700 is preferably driven from supply 300 through a coupling (not shown) that includes a voltage regulator (not shown). An exemplary voltage regulator is the LM340 3-terminal positive regulator, available from the National Semiconductor Corporation, Santa Clara, Calif. The teachings of the LM340 datasheet are hereby incorporated by reference. Those of skill in the art will appreciate that most microcontrollers, and many other independently powered digital integrated circuits, are rated for no more than a 5 Volt power source. The clock frequency of microcontroller IC2 400 is set by crystal 480, coupled through appropriate pins. Pin 490 is the microcontroller IC2 400 ground reference.

Switch 600 is a twelve position dip switch that may be alterably and mechanically set to uniquely identify the microcontroller IC2 400. When individual ones of the twelve mechanical switches within dip switch 600 are closed, a path is generated from corresponding pins 650 on microcontroller IC2 400 to ground 690. Twelve switches create 2^{12} possible settings, allowing any microcontroller IC2 400 to take on one of 4096 different IDs, or addresses. In the preferred embodiment, only nine switches are actually used because the DMX-512 protocol, discussed below, is employed.

Once switch 600 is set, microcontroller IC2 400 "knows" its unique address ("who am I"), and "listens" on serial line 520 for a data stream specifically addressed to it. A high speed network protocol, preferably a DMX protocol, is used to address network data to each individually addressed microcontroller IC2 400 from a central network controller (not shown). The DMX protocol is described in a United States Theatre Technology, Inc. publication entitled "DMX512/1990 Digital Data Transmission Standard for Dimmers and Controllers," incorporated herein by reference. Basically, in the network protocol used herein, a central controller (not shown) creates a stream of network data consisting of sequential data packets. Each packet first contains a header, which is checked for conformance to the standard and discarded, followed by a stream of sequential bytes representing data for sequentially addressed devices. For instance, if the data packet is intended for light number fifteen, then fourteen bytes from the data stream will be discarded, and the device will save byte number fifteen. If as in the preferred embodiment, more than one byte is needed, then the address is considered to be a starting address, and more than one byte is saved and utilized. Each byte corresponds to a decimal number 0 to 255, linearly representing the desired intensity from Off to Full. (For simplicity, details of the data packets such as headers and stop bits are omitted from this description, and will be well appreciated by those of skill in the art.) This way, each of the three LED colors is assigned a discrete intensity value between 0 and 255. These respective intensity values are stored in respective registers within the memory of microcontroller IC2 400 (not shown). Once the central controller exhausts all data packets, it starts over in a continuous refresh cycle. The refresh cycle is define by the standard to be a minimum of 1196 microseconds, and a maximum of 1 second.

Microcontroller IC2 400 is programmed continually to "listen" for its data stream. When microcontroller IC2 400 is "listening," but before it detects a data packet intended for it, it is running a routine designed to create the square wave signal outputs on pins 434, 454 and 474. The values in the color registers determine the duty cycle of the square wave. Since each register can take on a value from 0 to 255, these values create 256 possible different duty cycles in a linear range from 0% to 100%. Since the square wave frequency is uniform and determined by the program running in the microcontroller IC2 400, these different discrete duty cycles represent variations in the width of the square wave pulses. This is known as pulse width modulation (PWM).

The PWM interrupt routine is implemented using a simple counter, incrementing from 0 to 255 in a cycle during each period of the square wave output on pins 434, 454 and 474. When the counter rolls over to zero, all three signals are set high. Once the counter equals the register value, signal output is changed to low. When microcontroller IC2 400 receives new data, it freezes the counter, copies the new data to the working registers, compares the new register values with the current count and updates the output pins accordingly, and then restarts the counter exactly where it left off. Thus, intensity values may be updated in the middle of the PWM cycle. Freezing the counter and simultaneously updating the signal outputs has at least two advantages. First, it allows each lighting unit to quickly pulse/strobe as a strobe light does. Such strobing happens when the central controller sends network data having high intensity values alternately with network data having zero intensity values at a rapid rate. If one restarted the counter without first updating the signal outputs, then the human eye would be able to perceive the staggered deactivation of each individual color LED that is set at a different pulse width. This feature is not of concern in incandescent lights because of the integrating effect associated with the heating and cooling cycle of the illumination element. LEDs, unlike incandescent elements, activate and deactivate essentially instantaneously in the present application. The second advantage is that one can "dim" the LEDs without the flickering that would otherwise occur if the counter were reset to zero. The central controller can send a continuous dimming signal when it creates a sequence of intensity values representing a uniform and proportional decrease in light intensity for each color LED. If one did not update the output signals before restarting the counter, there is a possibility that a single color LED will go through nearly two cycles without

experiencing the zero current state of its duty cycle. For instance, assume the red register is set at 4 and the counter is set at 3 when it is frozen. Here, the counter is frozen just before the "off" part of the PWM cycle is to occur for the red LEDs. Now assume that the network data changes the value in the red register from 4 to 2 and the counter is restarted without deactivating the output signal. Even though the counter is greater than the intensity value in the red register, the output state is still "on", meaning that maximum current is still flowing through the red LEDs. Meanwhile, the blue and green LEDs will probably turn off at their appropriate times in the PWM cycle. This would be perceived by the human eye as a red flicker in the course of dimming the color intensities. Freezing the counter and updating the output for the rest of the PWM cycle overcomes these disadvantages, ensuring the flicker does not occur.

The network interface for microcontroller IC2 **400** will now be described. Jacks **800** and **900** are standard RJ-8 network jacks. Jack **800** is used as an input jack, and is shown for simplicity as having only three inputs: signal inputs **860**, **870** and ground **850**. Network data enters jack **800** and passes through signal inputs **860** and **870**. These signal inputs are then coupled to IC3 **500**, which is an RS-485/RS-422 differential bus repeater of the standard type, preferably a DS96177 from the National Semiconductor Corporation, Santa Clara, Calif. The teachings of the DS96177 datasheet are hereby incorporated by reference. The signal inputs **860**, **870** enter IC3 **500** at pins **560**, **570**. The data signal is passed through from pin **510** to pin **520** on microcontroller IC2 **400**. The same data signal is then returned from pin **540** on IC2 **400** to pin **530** on IC3 **500**. Jack **900** is used as an output jack and is shown for simplicity as having only five outputs: signal outputs **960**, **970**, **980**, **990** and ground **950**. Outputs **960** and **970** are split directly from input lines **860** and **870**, respectively. Outputs **980** and **990** come directly from IC3 **500** pins **580** and **590**, respectively. It will be appreciated that the foregoing assembly enables two network nodes to be connected for receiving the network data. Thus, a network may be constructed as a daisy chain, if only single nodes are strung together, or as a binary tree, if two nodes are attached to the output of each single node.

From the foregoing description, one can see that an addressable network of LED illumination or display units can be constructed from a collection of power modules each connected to a respective light module. As long as at least two primary color LEDs are used, any illumination or display color may be generated simply by preselecting the light intensity that each color emits. Further, each color LED can emit light at any of 255 different intensities, depending on the duty cycle of PWM square wave, with a full intensity pulse generated by passing maximum current through the LED. Further still, the maximum intensity can be conveniently programmed simply by adjusting the ceiling for the maximum allowable current using programming resistances for the current regulators residing on the light module. Light modules of different maximum current ratings may thereby be conveniently interchanged.

The foregoing embodiment may reside in any number of different housings. A preferred housing for an illumination unit is described. Turning now to FIG. **3**, there is shown an exploded view of an illumination unit of the present invention comprising a substantially cylindrical body section **10**, a light module **20**, a conductive sleeve **30**, a power module **40**, a second conductive sleeve **50**, and an enclosure plate **60**. It is to be assumed here that the light module **20** and the power module **40** contain the electrical structure and software of light module **100** and power module **200**, described above. Screws **62**, **64**, **66**, **68** allow the entire apparatus to be mechanically connected. Body section **10**, conductive sleeves **30** and **50** and enclosure plate **60** are preferably made from a material that conducts heat, most preferably aluminum. Body section **10** has an open end, a reflective interior portion and an illumination end, to which module **20** is mechanically affixed. Light module **20** is disk shaped and has two sides. The illumination side (not shown) comprises a plurality of LEDs of different primary colors. The connection side holds an electrical connector male pin assembly **22**. Both the illumination side and the connection side are coated with aluminum surfaces to better allow the conduction of heat outward from the plurality of LEDs to the body section **10**. Likewise, power module **40** is disk shaped and has every available surface covered with aluminum for the same reason. Power module **40** has a connection side holding an electrical connector female pin assembly **44** adapted to fit the pins from assembly **22**. Power module **40** has a power terminal side holding a terminal **42** for connection to a source of DC power. Any standard AC or DC jack may be used, as appropriate.

Interposed between light module **20** and power module **40** is a conductive aluminum sleeve **30**, which substantially encloses the space between modules **20** and **40**. As shown, a diskshaped enclosure plate **60** and screws **62**, **64**, **66** and **68** seal all of the components together, and conductive sleeve **50** is thus interposed between enclosure plate **60** and power module **40**. Once sealed together as a unit, the illumination apparatus may be connected to a data network as described above and mounted in any convenient manner to illuminate an area. In operation, preferably a light diffusing means will be inserted in body section **10** to ensure that the LEDs on light module **20** appear to emit a single uniform frequency of light.

From the foregoing, it will be appreciated that PWM current control of LEDs to produce multiple colors may be incorporated into countless environments, with or without networks. For instance, FIG. **8** shows a hand-held flashlight can be made to shine any conceivable color using an LED assembly of the present invention. The flashlight contains an external adjustment means **5**, that may be for instance a set of three potentiometers coupled to an appropriately programmed microcontroller through respective A/D conversion means **15**. Each potentiometer would control the current duty cycle, and thus the illumination intensity, of an individual color LED on LED board **25**. With three settings each capable of generating a different byte from 0 to 255, a computer-controlled flashlight may generate twenty-four bit color. Of course, three individual potentiometers can be incorporated into a single device, such as a track ball or joystick, so as to be operable as a single adjuster. Further, it is not necessary that the adjustment means must be a potentiometer. For instance, a capacitive or resistive thumb plate may also be used to program the two or three registers necessary to set the color. A non-hand held embodiment of the present invention may be used as an underwater swimming pool light. Since the present invention can operate at relatively low voltages and low current, it is uniquely suited for safe underwater operation.

Similarly, the present invention may be used as a general indicator of any given environmental condition. FIG. **9** shows the general functional block diagram for such an apparatus. Shown within FIG. **9** is also an exemplary chart showing the duty cycles of the three color LEDs during an exemplary period. As one example of an environmental indicator, the power module can be coupled to an inclinom-

eter. The inclinometer measures general angular orientation with respect to the earth's center of gravity. The inclinometer's angle signal can be converted through an A/D converter and coupled to the data inputs of the microcontroller in the power module. The microcontroller can then be programmed to assign each discrete angular orientation a different color through the use of a lookup table associating angles with LED color register values. The "color inclinometer" may be used for safety, such as in airplane cockpits, or for novelty, such as to illuminate the sails on a sailboat that sways in the water. Another indicator use is to provide an easily readable visual temperature indication. For example, a digital thermometer can be connected to provide the microcontroller a temperature reading. Each temperature will be associated with a particular set of register values, and hence a particular color output. A plurality of such "color thermometers" can be located over a large space, such as a storage freezer, to allow simple visual inspection of temperature over three dimensions.

Another use of the present invention is as a lightbulb. Using appropriate rectifier and voltage transformation means, the entire power and light modules may be placed in an Edison-mount (screw-type) lightbulb housing. Each bulb can be programmed with particular register values to deliver a particular color bulb, including white. The current regulator can be pre-programmed to give a desired current rating and thus preset light intensity. Naturally, the lightbulb will have a transparent or translucent section that allows the passage of light into the ambient.

While the foregoing has been a detailed description of the preferred embodiment of the invention, the claims which follow define more freely the scope of invention to which applicant is entitled. Modifications or improvements which may not come within the explicit language of the claims described in the preferred embodiments should be treated as within the scope of invention insofar as they are equivalent or otherwise consistent with the contribution over the prior art and such contribution is not to be limited to specific embodiments disclosed.

I claim:

1. Light apparatus comprising:

a power terminal;

at least one LED coupled to the power terminal;

a switch coupled to the at least one LED, the switch comprising an input responsive to an activation signal to enable flow of current through the switch;

an addressable controller having an alterable address, the controller coupled to the input and the controller generating the activation signal for a portion of a timing cycle;

the addressable controller further comprising a network interface that receives data corresponding to the alterable address, the portion of the timing cycle responsive to the received data;

a second LED coupled to the power terminal and the switch;

the switch comprising a second input corresponding to the second LED and responsive to a second activation signal; and

the addressable controller generating the second activation signal for a second portion of the timing cycle, and further receiving data from the network interface corresponding to the alterable address, the second portion of the timing cycle responsive to the received data.

2. The light apparatus of claim **1** wherein the at least one LED and the second LED comprise different colors.

3. The light apparatus of claim **1** wherein the first portion and the second portion represent respective duty cycles of PWM signals and the timing cycles are PWM periods.

4. A lighting network comprising a controller and a plurality of uniquely addressable illumination units, each unit comprising a first color LED and a second color LED, and each unit further comprising:

a network interface that receives from the controller network data comprising LED intensity values addressed to one of the uniquely addressable illumination units and corresponding to respective ones of the first color and the second color LED;

a memory that stores intensity values within the network data corresponding to the first color LED and to the second color LED;

a controller that generates a first pulse width modulated signal and a second pulse width modulated signal, both first and second signals having a duty cycle corresponding to the respective intensity values, whereby each of the first and second pulse width modulated signals is alternately in high voltage or a low voltage state;

a switch that directs current to the first color LED when the first pulse width modulated signal is in one of either the high voltage or the low voltage state, and that directs current to the second color LED when the second pulse width modulated signal is in one of either the high voltage or the low voltage state.

5. The network of claim **4** wherein each unit includes a plurality of first color LEDs and a plurality of second color LEDs.

6. The network of claim **5** wherein the first color LED and the second color LED are respectively a first primary color LED and a second primary color LED.

7. The network of claim **5** wherein each unit includes a third color LED, the intensity values addressed to an individual illumination unit further correspond to the third color LED, the controller further generates a third pulse width modulated signal having a duty cycle corresponding to the third color LED intensity value, whereby the third pulse width modulated signal is alternately in a high voltage or a low voltage state, and the switch further directs current to the third color LED when the third pulse width modulated signal is in one of either the high voltage or the low voltage state.

8. The network of claim **7** wherein the first color, the second color and the third color are different primary colors.

9. The network of claim **5** wherein the lighting network further comprises a repeater adapted to electrically interconnect each unit to at least two other units to form a path for the network data.

10. The network of claim **9** wherein the repeater is adapted to electrically interconnect each unit to one network data input and to two network data outputs.

11. An illumination apparatus comprising:

a plurality of LEDs of at least two different colors adapted to be coupled to a power source and to a common potential reference;

a switching device interposed between the plurality of LEDs and the common potential reference, the switching device comprising at least two switches corresponding to respective current paths of the at least two different color LEDs;

a controller that opens and closes the at least two switches according to a predetermined duty cycle;

a hand-held housing comprising a compartment for containing the power source and common reference

potential, and further comprising a lens assembly for reflecting the light emitted from the plurality of LEDs, which housing substantially encloses the plurality of LEDs, the switching device, and the controller; and

an adjustment device that receives user input, the adjustment device coupled to the controller and providing to the controller, in response to the user input, information to program respective duty cycles, for each color of the at least two different color LEDs, wherein the duty cycle ranges from a minimum to a maximum, and the adjustment device is adapted to generate a range of duty cycles between the minimum and the maximum.

12. An illumination apparatus comprising:

a plurality of LEDs of at least two different colors;

a switch coupled to the plurality of LEDs, the switch including an input corresponding to each one of the plurality of LEDs, the switch controllably coupling each of the plurality of LEDs between a DC power source and a common potential reference in response to an activation signal applied to the input;

a controller that generates the activation signal for the input corresponding to each one of the plurality of LEDs;

a housing comprising a compartment for containing the DC power source and the common reference potential, and the housing substantially enclosing the plurality of LEDs, the switch, and the controller; and

an adjustment device that receives user input, the adjustment device coupled to the controller and providing to the controller, in response to the user input, signals to program the activation signal for the input corresponding to each one of the plurality of LEDs.

13. An illumination apparatus comprising:

a plurality of LEDs of at least two different colors adapted to be coupled to a power source and to a common potential reference;

a switching device interposed between the plurality of LEDs and the common potential reference, the switching device comprising at least two switches corresponding to respective current paths of the at least two different color LEDs;

a controller that opens and closes the at least two switches according to a predetermined duty cycle; and

a hand-held housing comprising a compartment for containing the power source and common reference potential, and further comprising a lens assembly for reflecting the light emitted from the plurality of LEDs, which housing substantially encloses the plurality of LEDs, the switching device, and the controller.

14. An illumination apparatus comprising:

a plurality of LEDs of at least two different colors adapted to be coupled to a power source and to a common potential reference;

a switching device interposed between the plurality of LEDs and the power source, the switching device comprising at least two switches corresponding to respective current paths of the at least two different color LEDs;

a controller that opens and closes the at least two switches according to a predetermined duty cycle; and

a hand-held housing comprising a compartment for containing the power source and common reference potential, and further comprising a lens assembly for reflecting the light emitted from the plurality of LEDs, which housing substantially encloses the plurality of LEDs, the switching device, and the controller.

15. A light apparatus comprising:

a power terminal;

at least one LED coupled to the power terminal;

a switch coupled to the at least one LED, the switch comprising an input responsive to an activation signal that enables flow of current through the at least one LED; and

a controller having an alterable address, the controller coupled to the input and having a timer that generates the activation signal for a predefined portion of a timing cycle, the controller further including a network interface that receives data corresponding to the alterable address and indicative of the predefined portion of the timing cycle.

16. The light apparatus of claim **15** wherein the predefined portion represents the duty cycle of a PWM signal and the timing cycle is the PWM period.

17. An illumination apparatus comprising:

a plurality of LEDs of at least two different colors adapted to be coupled to a power source and to a common potential reference;

a switching device interposed between the plurality of LEDs and the common potential reference, the switching device comprising at least two switches corresponding to respective current paths of the at least two different color LEDs;

a controller that opens and closes the at least two switches and that generates one or more duty cycles thereby; and

a user input coupled to the controller that programs the controller to generate the one or more duty cycles.

18. The apparatus of claim **17** wherein one of the one or more duty cycle ranges from a minimum to a maximum, and the user input is adapted to generate a substantially continuous range of duty cycles between the minimum and the maximum.

19. The apparatus of claim **17** wherein the user input includes a potentiometer for each color of the at least two different color LEDs, each potentiometer having an independently adjustable setting, and the user input includes an analog-to-digital converter for converting each independently adjustable setting into a numerical value indicative of one of the one or more duty cycles.

20. The apparatus of claim **17** further comprising a housing that substantially encloses the plurality of LEDs, the switching device, the controller, and the user input.

21. The apparatus of claim **20** wherein the housing is hand-held.

22. A light apparatus comprising:

a voltage regulator that converts an AC potential into a DC power source;

a plurality of LEDs of at least two different colors adapted to be coupled to the DC power source and to a common potential reference;

a light-transmitting enclosure surrounding the plurality of LEDs;

a current sink interposed between the plurality of LEDs and the common potential reference, the current sink comprising at least two switches corresponding to respective current paths of the at least two different color LEDs;

a controller that opens and closes the at least two switches and generates a duty cycle thereby.

23. The light apparatus of claim **22** wherein the duty cycle is predefined and uniform, whereby the light apparatus permanently generates a single unalterable color of light.

24. A light apparatus comprising:

a voltage regulator that converts an AC potential into a DC power source;

a plurality of LEDs of at least two different colors adapted to be coupled to the DC power source and to a common potential reference;

a light-transmitting enclosure surrounding the plurality of LEDs;

a switching device in series with the plurality of LEDs and between the common potential reference and the DC power source, the switching device including at least two switches corresponding to respective current paths of the at least two different color LEDs; and

a controller that opens and closes the at least two switches according to a duty cycle.

25. A light apparatus comprising:

a plurality of LEDs of at least two different colors adapted to be coupled to a power source and to a common potential reference;

a switching device interposed between the plurality of LEDs and the common potential reference, the switching device comprising at least two switches corresponding to respective current paths of the at least two different color LEDs;

a controller that opens and closes the at least two switches according to a predetermined duty cycle; and

a housing adapted for use as an underwater light, the housing comprising a compartment for containing the power source and common reference potential, and further comprising a lens assembly for reflecting the light emitted from the plurality of LEDs, which housing substantially encloses the plurality of LEDs, the switching device, and the controller.

26. A light apparatus comprising:

a plurality of LEDs of at least two different colors adapted to be coupled to a power source and to a common potential reference;

a switching device interposed between the plurality of LEDs and the power source, the switching device including at least two switches corresponding to respective current paths of the at least two different color LEDs;

a controller that opens and closes the at least two switches according to a predetermined duty cycle; and

a housing adapted for use as an underwater light, the housing comprising a compartment for containing the power source and common reference potential, and further comprising a lens assembly for reflecting the light emitted from the plurality of LEDs, which housing substantially encloses the plurality of LEDs, the switching device, and the controller.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,806,659 B1
DATED : October 19, 2004
INVENTOR(S) : George G. Mueller and Ihor A. Lys

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

<u>Title page,</u>
Item [56], **References Cited**, U.S. PATENT DOCUMENTS, replace so it reads:

-- 2,909,097 A	10/1959	Alden et al.
3,318,185 A	5/1967	Kott
3,595,991 A	7/1971	Diller
3,740,570 A	6/1973	Kaelin et al.

(List continued on next page.) --

Signed and Sealed this

Twenty-sixth Day of April, 2005

JON W. DUDAS
Director of the United States Patent and Trademark Office

US008207541B2

(12) United States Patent
Van Herpen et al.

(10) **Patent No.: US 8,207,541 B2**
(45) **Date of Patent: Jun. 26, 2012**

(54) **LIGHT OUTPUT DEVICE**

(75) Inventors: **Maarten Marinus Johannes Wilhelmus Van Herpen**, Eindhoven (NL); **Markus Cornelius Vermeulen**, Eindhoven (NL)

(73) Assignee: **Koninklijke Philips Electronics N.V.**, Eindhoven (NL)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 304 days.

(21) Appl. No.: **12/594,641**

(22) PCT Filed: **Apr. 7, 2008**

(86) PCT No.: **PCT/IB2008/051311**

§ 371 (c)(1), (2), (4) Date: **Oct. 5, 2009**

(87) PCT Pub. No.: **WO2008/126003**

PCT Pub. Date: **Oct. 23, 2008**

(65) **Prior Publication Data**

US 2010/0244695 A1 Sep. 30, 2010

(30) **Foreign Application Priority Data**

Apr. 12, 2007 (EP) 07106007

(51) **Int. Cl.**
H01L 29/18 (2006.01)

(52) **U.S. Cl.** ... **257/88**; 257/99; 362/249.02; 362/249.05

(58) **Field of Classification Search** 257/88, 257/99; 362/227, 249.01, 249.02, 249.05
See application file for complete search history.

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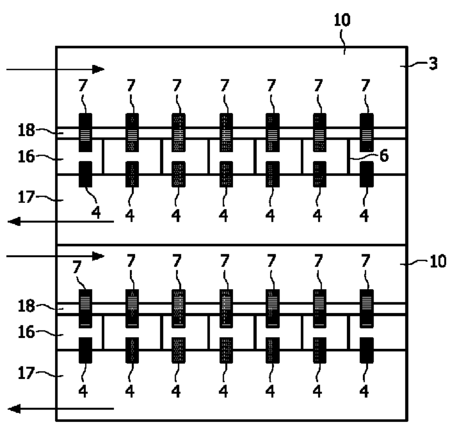
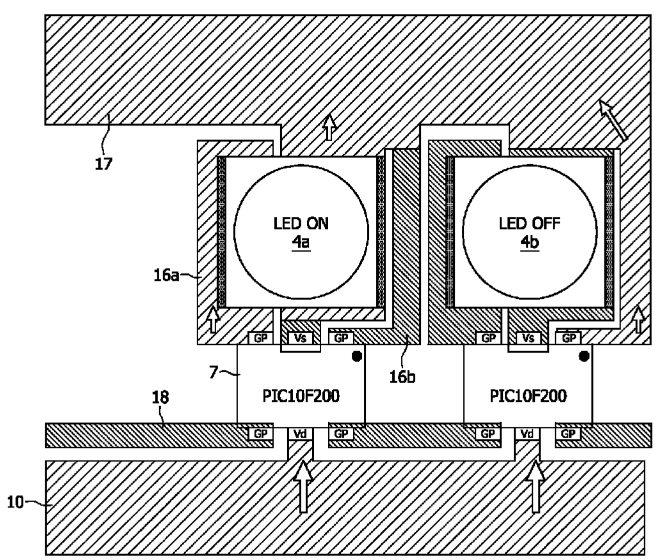
Primary Examiner — Thuy Vinh Tran
(74) *Attorney, Agent, or Firm* — Mark L. Beloborodov

(57) **ABSTRACT**

A light output device comprises a substrate arrangement and a plurality of light source devices (**4**) integrated into the structure of the substrate arrangement. A respective control circuit (**7**) is provided for one or more light source devices (**4**) and also integrated into the structure of the substrate arrangement. Control circuits are embedded with the light source devices into the structure of the substrate. This enables a shared control line or lines (**18**) to be used to control a group of light source devices.

16 Claims, 5 Drawing Sheets





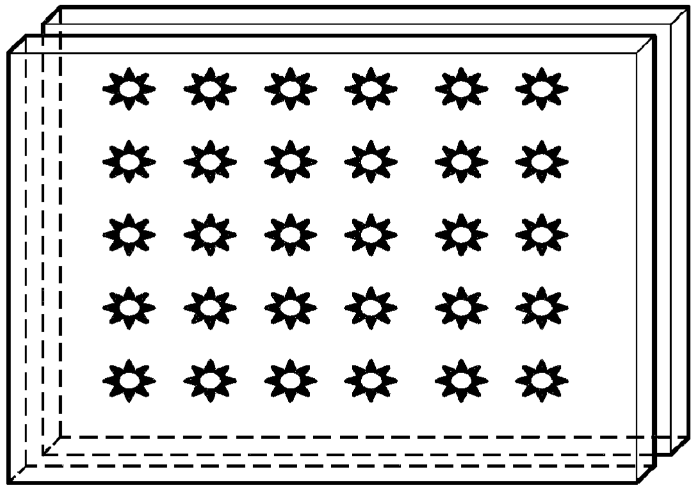


FIG. 1
PRIOR ART

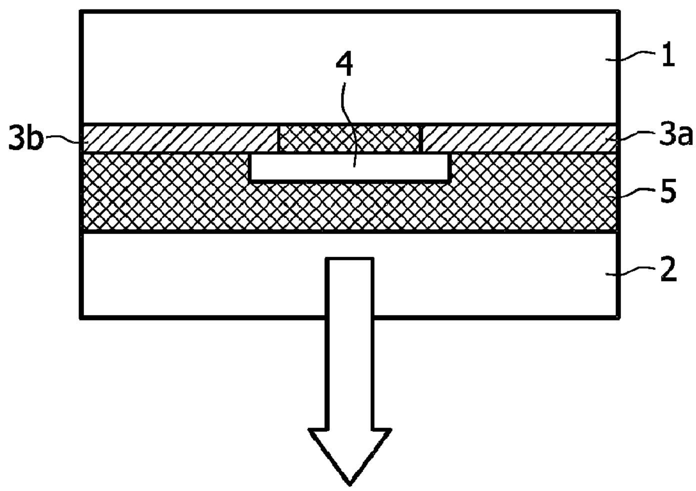


FIG. 2
PRIOR ART

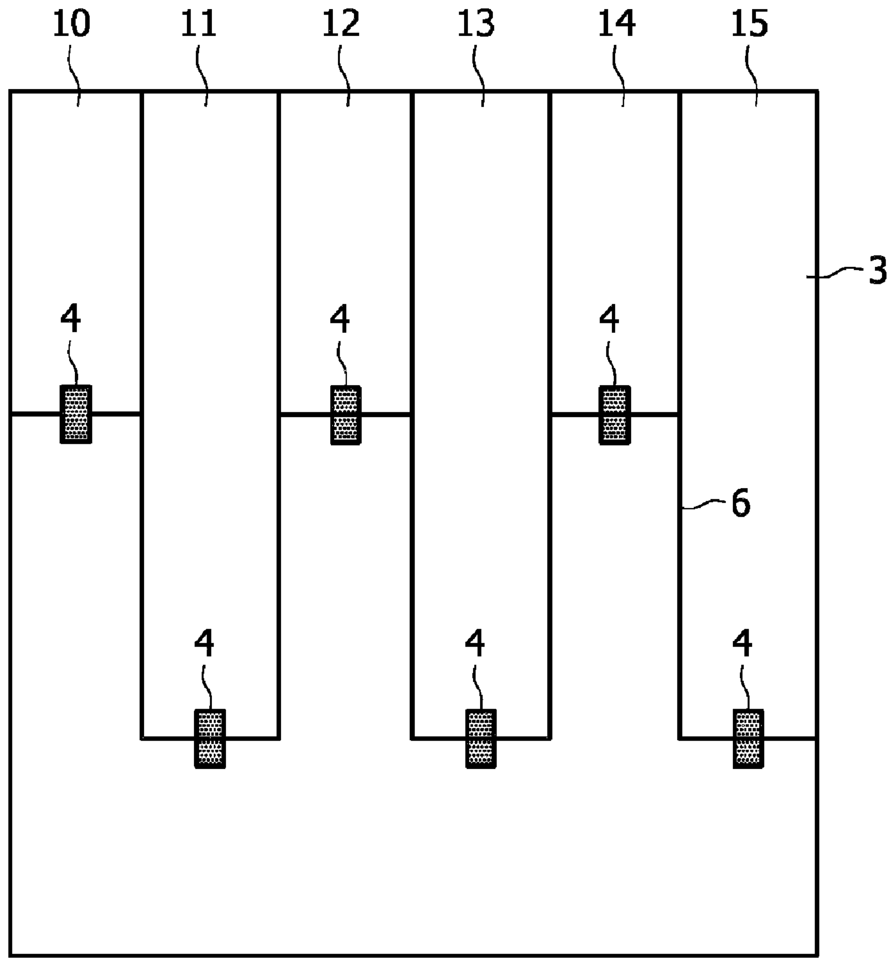


FIG. 3
PRIOR ART

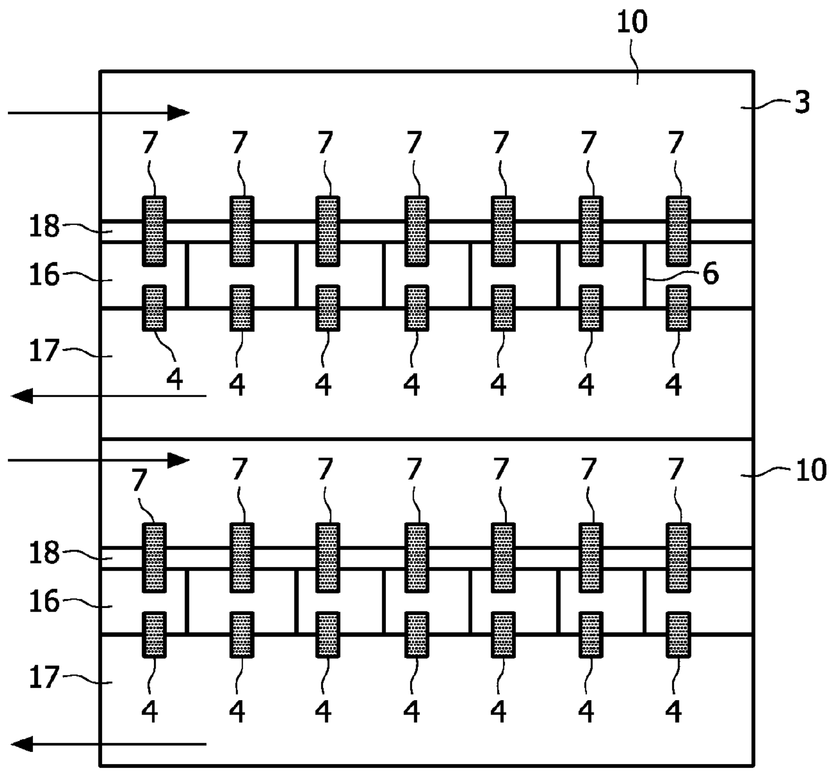


FIG. 4

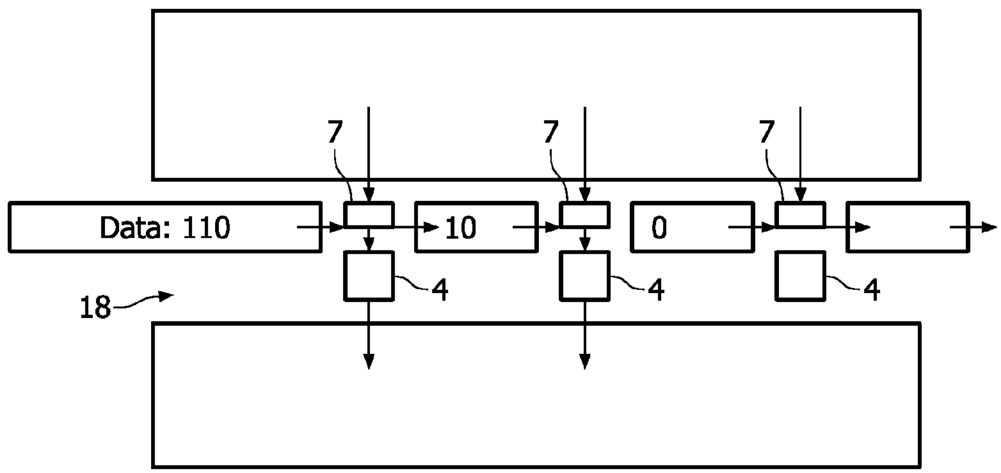
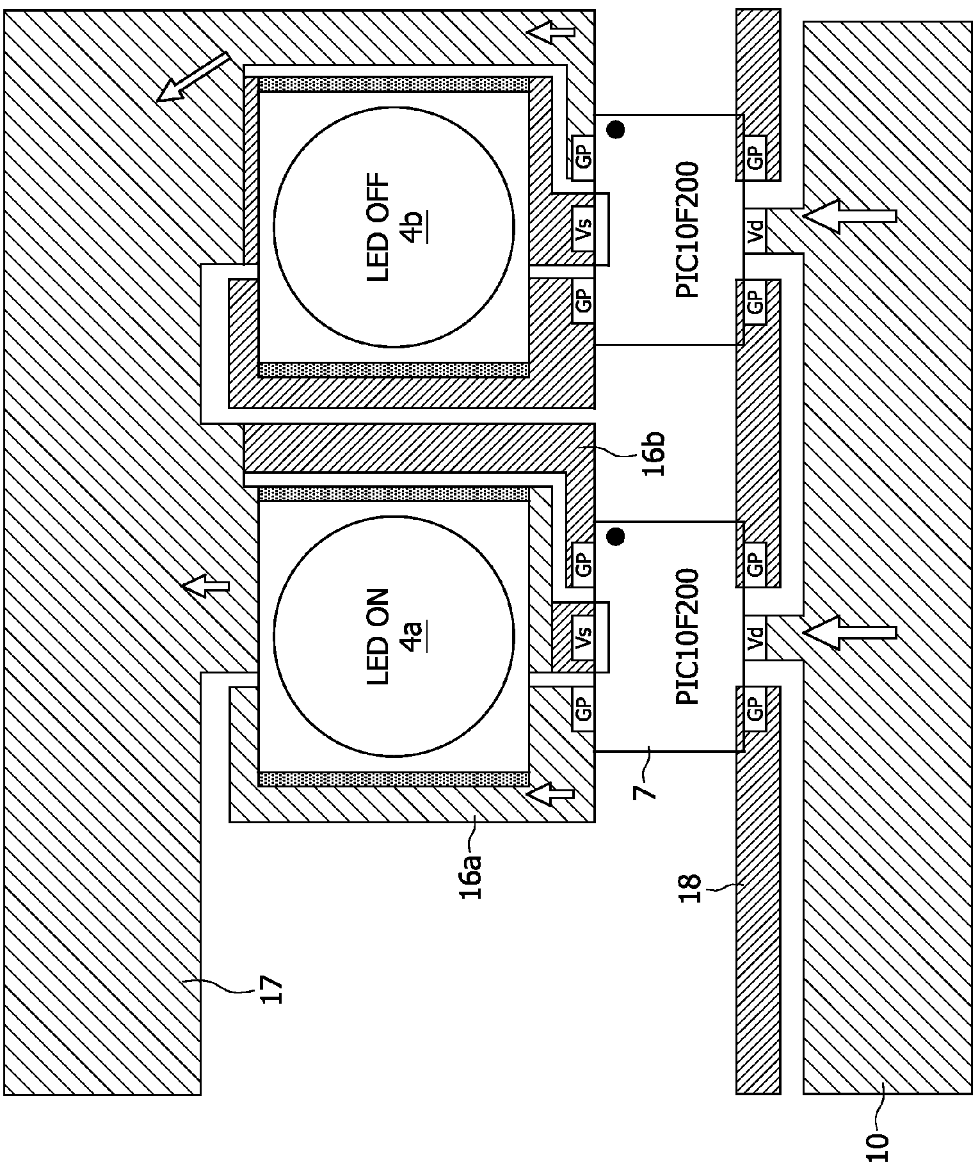


FIG. 5

FIG. 6


LED OFF
4b
LED ON
4a
PIC10F200
PIC10F200
GP
Vs
Vd
16a
16b
7
18
17
10

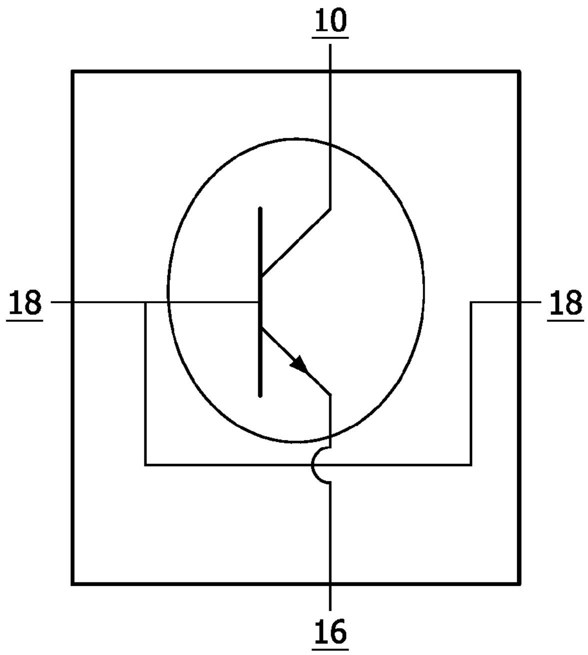


FIG. 7

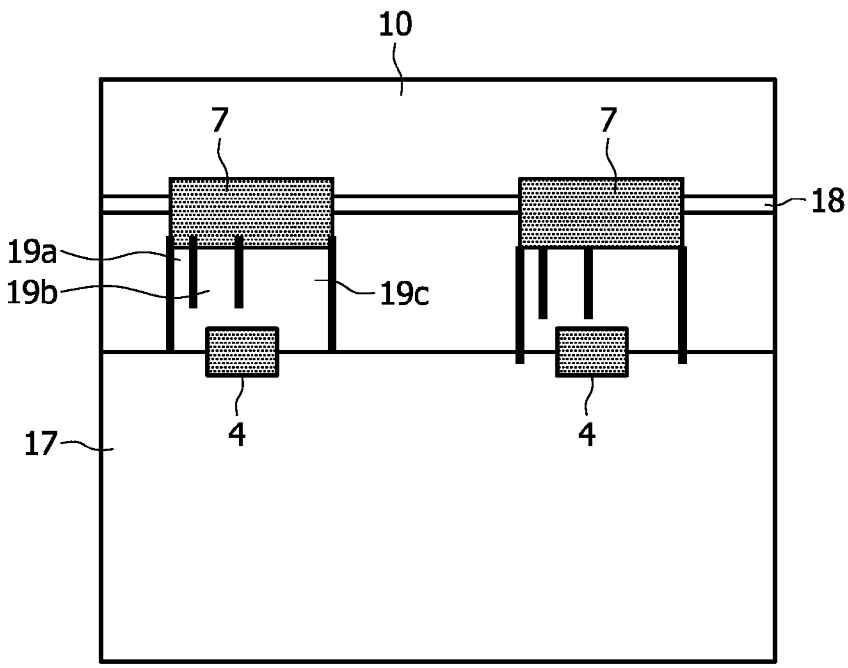


FIG. 8

LIGHT OUTPUT DEVICE

This invention relates to light output devices, in particular using discrete light sources associated with a transparent substrate structure.

TECHNICAL BACKGROUND

One known example of this type of lighting device is a so-called "LED in glass" device. An example is shown in FIG. **1**. Typically a glass plate is used, with a transparent conductive coating (for example ITO) forming electrodes. The conductive coating is patterned in order to make the electrodes, that are connected to a semiconductor LED device. The assembly is completed by laminating the glass, with the LEDs inside a thermoplastic layer (for example polyvinyl butyral, PVB).

Applications of this type of device are shelves, showcases, facades, office partitions, wall cladding, and decorative lighting. The lighting device can be used for illumination of other objects, for display of an image, or simply for decorative purposes. One problem with this type of device is that it is difficult to provide a structure which enables individual LEDs in the glass to be turned on and off, for example in order to display an image, or a dynamic pattern. This is difficult, because a two-dimensional pattern of transparent electrodes is desired, but crossovers need to be avoided if the layer structure is to be kept simple. if individual wires are used for each LED (instead of a two dimensional pattern), this results in very high wire resistances (for example ITO electrodes), leading to high electrical losses in these wires.

SUMMARY OF THE INVENTION

It is an object of the invention to provide independent control of the light source devices or a group thereof, but with a relatively simple conductor pattern.

According to the invention, there is provided a light output device comprising: a substrate arrangement;

a plurality of light source devices integrated into the structure of the substrate arrangement;

a plurality of control circuits associated with the light source devices and also integrated into the structure of the substrate arrangement,

wherein each control circuit comprises at least four connected connectors, with at least one connector coupled to one or more respective light source devices.

The invention provides control circuits embedded with the light source devices into the structure of the substrate. The control circuits can share connections (such as power lines) and use a shared bus-type control system, and this arrangement can thereby avoid the need for large numbers of individual conductors.

The control circuit may have 5 or 6 connectors.

Preferably, each control circuit comprises an input to which an input voltage is provided, an output for controlling the respective one or more light source devices, a control input for receiving a control signal and a control output for outputting a control signal.

This enables control circuits to be coupled together using their control inputs and control outputs. In this way, they can be provided along a common control line or set of control lines, so that the control lines can be shared between the control circuits, or groups of control circuits.

The plurality of control circuits may be connected in a series, with the control output of one control circuit connected to the control input of the next control circuit. This enables a

single data line to be used to control a group of light source devices. The control signal is passed from circuit to circuit. This enables power lines (and control lines) to be defined with low resistance, wide tracks.

The control input of each control circuit is preferably adapted to receive a serial data signal and to control the switching of the input voltage to the output in dependence on one or more bits of the serial data signal. In this way, a serial data signal can be passed from control circuit to control circuit using a shared control signal line, to effect control of the multiple control circuits. For example, the control output of each control circuit can be adapted to output a serial data signal from which the one or more bits of the serial data signal have been removed. Thus, each control circuit responds to pre-allocated parts of the serial control word, and then removes these parts of the control word so that the next controller can respond to its control signal.

A drive electrode can be provided which is common to all of the plurality of control circuits and connected to each control circuit input. This can have a large area and therefore low resistance.

The output of each control circuit is preferably connected to a first terminal of the respective (two-terminal) light source device, and the device preferably further comprises a drain electrode which is common to all of the plurality of light source devices and connected to a second terminal of each light source device. Again, this can be a large area low resistance electrode.

The device may comprise a two dimensional array of light source devices and associated control circuits, wherein the light source devices and control circuits are divided into groups, each group comprising a plurality of light source devices and control circuits and a common drive electrode connected to each control circuit input. Each group also preferably comprises a common drain electrode connected to each light source device. For example, a row and column array of light source devices can be provided.

Each group can then comprise a row or column, and the common drive electrode and the common drain electrodes are also row or column lines.

The common drive electrodes of each group can be coupled together and the common drain electrodes of each group can be coupled together, for example at the edge of the array, essentially placing groups in parallel.

Alternatively, the drain electrode of a first group can be connected to the drive electrode of the second group, essentially placing groups in series.

Each control circuit may comprise a microcontroller.

In one example, each control circuit can comprise a plurality of outputs, each having a different resistance, or a different function. This enables for example different light source device brightness to be provided, by introducing different amounts of series resistance between the output of the control circuit and the light source device. It also enables for example that a reference voltage near the control circuit is substantially independent of the on/off state of the light source.

The substrate arrangement can comprise first and second substrates and an electrode arrangement sandwiched between the substrates, wherein the at least one light source is connected to the electrode arrangement. This provides an embedded light source. For example, the light source devices can each comprise an LED device or a group of LED devices.

Each control circuit may switch power between either (i) a light source device or devices, or (ii) an output resistor. This enables the voltage supply lines to remain at stable voltages, as the currents flowing can remain substantially constant

regardless of whether the control circuit switches its associated light source device or devices on or off.

BRIEF DESCRIPTION OF THE DRAWINGS

Examples of the invention will now be described in detail with reference to the accompanying drawings, in which:

FIG. **1** shows a known LED in glass illumination device;

FIG. **2** shows a single LED of the device of FIG. **1** in more detail;

FIG. **3** shows one way to provide independent control of multiple light source devices;

FIG. **4** shows a first example of light output device of the invention;

FIG. **5** is used to explain further the operation of the device of FIG. **4**;

FIG. **6** shows an alternative connector layout design;

FIG. **7** shows alternative control circuit designs; and

FIG. **8** shows a second example of light output device of the invention.

The same reference numbers are used to denote similar parts in the different figures.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

The structure of an LED in glass illumination device is shown in FIG. **2**. The lighting device comprises glass plates **1** and **2**. Between the glass plates are (semi-) transparent electrodes **3***a* and **3***b* (for example formed using ITO), and a LED **4** connected to the transparent electrodes **3***a* and **3***b*. A layer of thermoplastic material **5** is provided between glass plates **1** and **2** (for example PVB or UV resin).

The glass plates typically may have a thickness of 1.1 mm-2.1 mm. The spacing between the electrodes connecting to the LED is typically 0.01-3 mm, for example around 0.15 mm. The thermoplastic layer has a typical thickness of 0.3 mm-2 mm, and the electrical resistance of the electrodes is in the range 2-80 Ohm, or 10-30 Ohms/square.

The electrodes are preferably substantially transparent, so that they are imperceptible to a viewer in normal use of the device. If the conductor arrangement does not introduce a variation in light transmission (for example because it is not patterned, or because the pattern cannot be seen), a transparency of greater than or equal to 50% may be sufficient for the system to be transparent. More preferably, the transparency is greater than 70%, more preferably 90%, and even more preferably 99%. If the conductor arrangement is patterned (for example because thin wires are used), the transparency is preferably greater than 80%, more preferably 90%, but most preferably greater than 99%.

The electrodes can be made of a transparent material such as ITO or they can be made of an opaque material such as copper but be sufficiently thin so that they are not visible in normal use. Examples of suitable materials are disclosed in U.S. Pat. No. 5,218,351.

FIG. **3** shows an example of an electrode pattern for controlling individual LEDs. Individual wires **10-15** are used to control several respective LEDs **4**. The wires are made using a laser to make cuts **6** in a layer of electrode material **3**. A problem with this solution is that the wires **10-15** are very thin, which results in a very high resistance, and accordingly in a high loss of electric power.

The current invention provides an alternative solution for controlling multiple light sources (such as LEDs) embedded in a substrate (such as glass). The control of individual light sources enables display of an image, or other dynamic pattern.

For example, the invention provides embedded microcontrollers for the light sources, in the substrate. A thin data-wire can then be used to control a full series of light sources.

FIG. **4** shows a first embodiment according to the present invention. In this arrangement, a single electrode **10** is used to supply power to all LEDs **4** in one row of a row and column array of LEDs.

In order to control whether or not a LED **4** is turned on, a microcontroller **7** is associated with each LED. The microcontroller **7** has four connections. One connection is connected to an input electrode **10** common for a plurality of microcontrollers, another connection is connected to an individual output electrode **16**. These define input and output signal terminals. In the example of FIG. **4**, the LED **4** is connected between a respective electrode output **16** and a common electrode **17**. Thus, the microcontroller **7** can control the on/off state of its corresponding LED **4** by selectively passing power from input electrode **10** to output electrode **16**, which then drives the LED **4**.

In order for the microcontroller **7** to determine whether or not to turn a LED **4** on, it uses data it receives from a data line **18**. This data line carries a serial data string which is used to control all of the microcontrollers in the line. The data line thus connects to a control input of the microcontroller **7**, and each microcontroller also has a control output, for passing the data string to the next microcontroller in a series arrangement.

FIG. **4** shows two rows of LEDs and control circuits. Each row has its own common power supply line **10** as a row line and common drain line **17** as another row line, but the common power lines can be connected together (for example at an edge of the array), and likewise, the common drain lines can be connected together. This avoids crossovers within the array area. Alternatively, the drain line **17** and the power line of the next row can be the same electrode (thus the drain line of the first and the power line of the second row are merged).

FIG. **5** shows in more detail how a string of data "110" is input to data line **18** and interpreted by the microcontrollers. The first microcontroller **7** uses the first symbol in this string "1" to determine that its corresponding LED **4** should be turned on. The microcontroller removes the first item in the data string, and forwards the remaining data "10" to the next microcontroller using the its control output, which defines the continuation of the data line **18**. Similarly, the next microcontroller turns the LED on, and forwards the data "0" to the final microcontroller, which turns its LED off.

In this embodiment, only one data line **18** is shown. However, multiple data lines **18**, or a combination of a data line and a low power supply for the microcontroller may be used.

As an example of a microcontroller, a 6-Pin, 8-Bit Flash Microcontroller can be used, for example PIC 10F200/202/204/206 by Microchip Technology Inc.

FIG. **6** shows in more detail how the system may be implemented in practice. In this embodiment, two additional problems related to the microcontroller are addressed. First, the microcontroller needs to be supplied with power, and second the power voltage on the microcontroller should stay within certain parameters.

Similar to the example described above, common electrodes **10** and **17** are provided with low resistance due to their large electrode width. The data line is again shown as **18**, and the microcontrollers **7** and LEDs **4***a* and **4***b* are shown. Based on the information given by data line **18**, the microcontroller

7 supplies output power to either electrodes **16***a* or **16***b*. If power is supplied to electrode **16***a*, the LED will turn on, as shown for LED **4***a* in FIG. **6**.

Alternatively, if power is supplied to electrode **16***b*, the LED will not turn on, but power flows through line **16***b* (as shown for LED **4***b*), which is chosen to have a high resistance, such that the voltage drop across the electrode **16***b* is similar to the voltage that would otherwise be used for the LED. Using this approach, it is possible to achieve a stable voltage on a reference connector pin Vs of the microcontroller.

The supply voltage for the microcontroller is based on the difference between the voltage on line **10** and on pin Vs, which is the output voltage of line **16***b*. In this example, the output voltage of **16***b* equals the voltage of line **10**, and thus the supply voltage is based on the voltage difference between 10 and 17. A stable voltage on lines **17** thus ensures a stable chip power supply.

The white arrows show the current flow paths, for turning LED **4***a* on and LED **4***b* off. The voltage at the output of the LEDs is the same (the voltage drop over the LED is 0 in the case of LED off, but as a result of the path **16***b*, the output voltage is unchanged), so that the voltages on lines **10** and **17**, and the supply voltage to the microcontroller, are stable.

An additional advantage of the embodiment shown in FIG. **6** is that failure of a LED does not lead to problems for the other LEDs. This is because all LEDs and microcontrollers are connected between the same electrodes **10** and **17** in parallel.

In general, the microcontroller **7** may be any other electrical component comprising at least 4 connectors, with at least 1 connector connected to the conductor arrangement connected to the light source. Preferably it uses 2 connections for conducting electrical power, and has at least one additional input and one additional output connection for control signals.

For example, a simplified device can comprise a transistor connected to the data line **18**, as shown in FIG. **7**. The data line switches the transistor on or off, and thereby effects switching between the common input **10** and unique output **16**.

Using the device from FIG. **7**, it is possible to control the on/off state of an image in the glass (the glass can either display an image, or the LEDs can be off).

In a further embodiment, the microcontroller and the LED can be combined. This may be implemented by incorporating the LED and microcontroller in one device. However, it is also possible to connect the LED to the microcontroller with a small wire. This small wire replaces electrode **16**. The advantage of this is that the resistance of electrode **16** is circumvented, leading to a further reduced loss of electrical power.

In a further embodiment, the microcontroller is also used to control the light intensity of the LED as shown in FIG. **8**. In the example shown, this is done using a microcontroller with several output connectors leading to three electrode lines **19***a*, **19***b*, and **19***c*. The width and length of electrode lines **16** is chosen such that lines **19***a*, **19***b*, and **19***c* have a different resistance. Preferably the resistance through path **19***b* (including the connection resistance to the LED) is half the resistance through **19***a*, and **19***c* half that of **19***b*.

If the microcontroller transmits power from the common input **10** to the first output **19***a*, the LED will have a certain light intensity. If instead the microcontroller transmits power through the second output **19***b*, the LED will emit more light (preferably twice as much). In order to achieve a desired light intensity, the microcontroller may be instructed to make combinations of voltage outputs to the different output terminals **19***a*, **19***b*, and **19***c*.

In this example three output connectors are used for the microcontroller, but in practice this number may vary.

Another method for controlling the intensity of a LED is achieved by periodically switching the LED on and off (e.g. using a method known in the art as pulse width modulation). In the current invention, this can be done locally by each control circuit. Based on the input signal the control circuit can locally modulate the on/off state of the LED, in order to control its brightness (or the input signal may be modulated). This method works especially well in a system such as FIG. **6**. The advantage of local modulation is that not the entire conductor arrangement needs to be modulated. This limits the generation of electromagnetic radiation, which would otherwise be generated by the entire conductor arrangement.

The examples above have shown the light paths associated with individual light sources. However, it will be understood that the invention is typically implemented as many LED devices, embedded in a large glass plate. A typical distance between the LEDs may be 1 cm to 10 cm, for example approximately 3 cm.

Each light source may also comprise a single LED or multiple LEDs and one control circuit may control multiple light sources. When one control circuit is for multiple light sources, they may be different colours, for example red, green and blue, thus defining colour sub-pixels of a single colour light source.

The examples above use glass substrates, but it will be apparent that plastic substrates may also be used.

A small number of possible materials to form the transparent (or at least semi-transparent) electrodes have been outlined above. Other examples can be found in U.S. Pat. No. 5,218,351, and include electrically conductive wires, with a diameter of approximately 0.1 mm spaced by about 10 mm or more, or with a diameter of approximately 20 um and spaced by 1 mm or more. The wires can be made from strands of gold, silver, copper, zinc or stainless steel. Alternatively, strands made of a resin such as polyester or nylon wires can be used, the outer surface of which is coated with metal by vapour deposition, metal plating or the like. Conductive films of vapour-deposited SiO2-indium alloy can also be used.

One particularly preferred material is a conductive ink, which can be deposited by inkjet or silkscreen printing. The ink includes fine metal particles, such as silver, and has a conductance of less than 0.1 Ohm/square/mil. A typical wire width using ink is 0.08 mm to 0.8 mm.

Other electrical components may additionally be embedded into the structure of the device.

The LED and the control circuit may be merged into one integrated device, or they may be connected with a low-resistance wire.

In the examples above, the control circuit is for controlling brightness. Another function of the control circuit may be a programmed sequence of on/off states. For example, the control circuit may be instructed to let the LED blink on/off with a period of 1 second. Alternatively, it may be instructed to randomly turn the LEDs on/off with a predetermined average frequency (e.g. 1 Hz). Alternatively, it may be instructed with a sequence of on/off states which it will keep playing from the start of this sequence.

Thus, the control circuits can be used to implement a variety of programmable optical functions and effects. A lighting controller for the overall device is provided for controlling these effects, for controlling the signals provided to the individual control circuits.

Various modifications will be apparent to those skilled in the art.

The invention claimed is:

1. A light output device comprising:
a substrate arrangement;
a plurality of light source devices integrated into the substrate arrangement;
a plurality of control circuits respectively associated with the plurality of light source devices and integrated into the substrate arrangement; and
an input power supply electrode and an output power drain electrode, the input power supply electrode being common to at least the plurality of control circuits and the output power drain electrode being common to at least the plurality of light source devices,
wherein each control circuit comprises at least four connected connectors, with at least one connector coupled to at least one respective light source device, and
wherein each control circuit is configured to selectively switch between
the at least one respective light source device
and an output resistor connected between the input power supply electrode and the output power drain electrode, providing power from the input power supply electrode to the selected one of the at least one respective light source device and the output resistor.

2. The device as claimed in claim **1**, wherein at least one control circuit comprises an input to which an input voltage is provided, an output for controlling the respective at least one light source device, a control input for receiving a control signal and a control output for outputting a control signal.

3. The device as claimed in claim **2**, wherein the control input of each control circuit is configured to receive the control signal in the form of a serial data signal and to control the switching of the input voltage to the output in dependence on one or more bits of the data signal.

4. The device as claimed in claim **2**, wherein the plurality of control circuits are connected in a series, with the control output of one control circuit connected to the control input of the next control circuit.

5. The device as claimed in claim **2**, wherein the output of each control circuit is connected to a first terminal of the respective light source device, and wherein the output power drain electrode is connected to a second terminal of each light source device of the plurality of light source devices.

6. The device as claimed in claim **5** wherein The plurality of light source devices and the associated plurality of control circuits are arranged in a two dimensional array, wherein the light source devices and control circuits are divided into groups, each group comprising a plurality of light source devices and associated control circuits and a common drive electrode connected to each control circuit input.

7. The device as claimed in claim **6**, wherein each group comprises a common drain electrode connected to each light source device.

8. The device as claimed in claim **6**, wherein each group comprises a row or column, and wherein the common drive electrode is a row or column line and the common drain electrode is a row or column line.

9. The device as claimed in claim **1**, wherein the substrate arrangement comprises first and second substrates and an electrode arrangement sandwiched between the first and second substrates, wherein the at least one light source device of the plurality of light source devices is connected to the electrode arrangement.

10. The device as claimed in claim **1**, wherein the each light source device of the plurality of light source devices comprises an LED device or a group of LED devices.

11. A light output device comprising:
a plurality of light source devices embedded in a substrate;
a plurality of controllers embedded in the substrate and configured to control corresponding light source devices of the plurality of light source devices in response to a control signal;
a power input electrode common to the plurality of controllers;
a power output electrode common to the plurality of light source devices; and
a data line connecting the plurality of controllers in series and configured to provide the control signal to the plurality of controllers, each controller of the plurality of controllers selectively connecting the corresponding light source device of the plurality of light source devices to the power input electrode in response to the control signal for selectively turning on the corresponding light source device.

12. The device of claim **11**, further comprising:
a plurality of high resistance paths corresponding to the plurality of controllers, each controller of the plurality of controllers selectively connecting the corresponding high resistance path of the plurality of high resistance paths to the power input electrode, bypassing the corresponding light source device, in response to the control signal for selectively turning off the corresponding light source device.

13. The device of claim **11**, wherein the control signal comprises a string of control data having a plurality of bits corresponding to the plurality of controllers, respectively.

14. The device of claim **11**, wherein the plurality of controllers and the corresponding plurality of light sources are connected in parallel with one another.

15. A light output device comprising:
first and second LEDs embedded in a substrate;
first and second microcontrollers embedded in the substrate and configured to control the first and second LEDs, respectively, in response to a control signal; and
a data line connecting the first microcontroller in series with the second microcontroller and configured to provide the control signal to the first and second microcontrollers, the first microcontroller selectively connecting the first LED to a power input electrode in response to a first bit of the control signal and the second microcontroller selectively connecting the second LED to the power input electrode in response to a second bit of the control signal.

16. The device of claim **15**, wherein the first microcontroller comprises a first connector connected to the power input electrode, a second connector connected to the first LED, a third connector connected to the data line to input the control signal, and a fourth connector connected to the data line to output the control signal, and
wherein the second microcontroller comprises a first connector connected to the power input electrode, a second connector connected to the second LED, a third connector connected to the data line to input the control signal from the first microcontroller, and a fourth connector connected to the data line to output the control signal.

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